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DEVELOPMENT OF ANTICIPATORY AUTOMOBILE CRASH SENSORS

U.S. Dept. of Transportation

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16. Abstract A comprehensive examination is carried out to determine the basic system constraints and required operational characteristics for anticipatory sensing of impending automobile crashes. This is followed by consideration of a wide variety of possible sensing techniques and selection of those deserving of further study. Two methods are chosen, microwave radar and ultrasonic sonar, and the advantages, weaknesses, and uncertain areas of both are delineated.

Realization of both sensors is described. The radar sensor, comprising standard microwave components and solid state circuitry, has been installed on a test vehicle for characterization. Results are promising, but preliminary; the complexity of the sensing task and the reliability demands on the system require extensive analysis and testing before a conclusion can be drawn as to overall viability.

The sonar approach is a translation of the radar sensor into acoustic form. Transducers have been the subject of particular study and modification. Preliminary results suggest that environmental considerations and adequate target discrimination will be the major problem areas.

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SECTION 1
INTRODUCTION

1.1 OBJECTIVES

The cost of deaths and injuries associated with motor vehicle accidents in the United States is extremely large. Increased auto usage, greater trip length, and higher collision velocities make it difficult to prevent further increase; reduction in absolute numbers is seen to be a very challenging task. The magnitude of the problem has made improvement of auto safety both an important subject and an explicit national goal. The problem is of course many-faceted, and numerous private and public agencies are involved. The focal point of these activities, the National Highway Traffic Safety Administration (NHTSA), has defined a large number of specific areas of particular impact on the automobile safety problem. One area of central importance is that of vehicle crashworthiness.

Although many steps are being taken to prevent the occurrence of collisions, it is unreasonable to suppose that a dramatic decrease can be brought about in a short time. Therefore it is both highly desirable and effective to do as much as possible to ensure that the occupants of a vehicle involved in an accident will sustain minimal injuries. This goal can be achieved relatively directly through influence on vehicle design and construction. One need not depend on the very lengthy and difficult processes of changing the thinking of the public, bringing about new legislation and improved enforcement, and developing better medical services.

Crashworthiness is in itself a large topic involving the total vehicle design. In part, proper use must be made of energy absorbing and deflecting structures (energy management) for both the vehicle-obstacle and occupant-vehicle collisions. The latter category is the "second collision", which occurs when the vehicle has been brought to a near-instantaneous stop and the occupants then impact the interior of the passenger compartment. It is here that the subject of occupant restraint systems arises.

It is useful to distinguish between systems which require passenger effort or cooperation as is the case for seat belts, and those which provide effective protection regardless of occupant actions. These are referred to as "active restraints" and "passive restraints", respectively. It has been the conclusion of NHTSA, based on much study, that current active systems (i.e., seatbelts), while extremely effective when utilized, are not used by a sufficient portion of the motoring

public to bring about the desired reduction in death and injury: nor is a marked change in this situation anticipated. Thus, interest has increasingly been focused on passive restraints, which, when perfected, can provide a measure of protection for the entire motoring public.

Deployable passive restraint systems, which in this report will be called dynamic passenger restraints, are now in the testing stage, and will soon be available on new automobiles. Present NHTSA motor vehicle safety regulations require the installation of passive restraint systems, providing basic crashworthiness for 30 mph barrier crashes, in passenger cars produced for the 1974 model year.*

In addition to dynamic restraints, other energy absorbing structures such as steering columns, dashboards, and windshields can legitimately be called passive restraints. To distinguish them from the dynamic systems, they will be referred to as static passive restraints. The investigation reported here relates directly to dynamic restraints only, and particularly to the function of collision sensing for triggering of deployment.

At present, the only type of dynamic restraint system to be subjected to extensive development and testing is the inflatable restraint - the "air bag". However, other techniques have been proposed and are under investigation, and this appears to be a fertile field for innovation. Different restraint systems can present significantly different triggering requirements, depending on the following factors:

a. <u>Deployment Time</u>. The rapidity with which a restraint can be deployed determines the minimum advance warning needed. Greater warning time can permit slower deployment, which may be desirable for maximum system effectiveness. In general, small cars and high impact velocities impose severe demands on the triggering if protection is to be effective.

b. <u>Deployment Duration</u>. The length of time which the restraint remains deployed is very important to overall protection. Since accidents can involve multiple

*Basic Crashworthiness" is defined operationally in terms of maximum allowed accelerations, forces, and pressures measured at various points on anthropometric dummies during actual barrier crashes.

collisions, it is desirable that the restraint be present for a period of one or more seconds. Therefore, a system which is operative for only a brief period should not be triggered any more in advance than necessary.

c. Penalty for Inadvertent Deployment. The task of discriminating between major and minor collisions is a difficult one, and errors can occur. A dynamic passive restraint system which can in itself cause injury or loss of control, or is costly to refit, requires a crash sensor which is almost totally free of unnecessary activation. Generally this can be accomplished only at the expense of excessive deployment time or outright failure to activate in some instances where restraints are needed. Should restraint systems be developed for which false alarms are physically, economically, and psychologically acceptable, the triggering decision could be based on different criteria and even different techniques.

d. Effectiveness of Static Restraints. The degree to which one can allow imperfect operation of dynamic restraints, particularly failure to operate, is strongly dependent upon the adequacy of the static restraints present. Energy absorbing steering columns and tempered/annealed windshields have already saved many lives. Decisions as to optimum deployment time, allowable false alarm rate, and other factors must include analysis of the compromise between static and dynamic protection. Similarly, the probability that seatbelts will be present and in use is important in determination of overall system characteristics. These criteria, in turn, affect the triggering requirements.

The viewpoint taken above was the determination of the triggering requirements from the restraint characteristics. An alternative viewpoint is to attempt to delineate what types of impending-collision sensors are feasible, and from their characteristics, develop specifications for the restraint system. Admittedly this approach is of limited utility. Even if one specifies an ideal sensor, the task of engineering a truly effective dynamic restraint has proven to be very challenging. Nonetheless, present systems were not developed in a vacuum; the feasibility and characteristics of mechanical sensors were always in the background. Also, the existence of certain sensor attributes imposes particular requirements on the restraints. In essence, the two aspects are intimately related and cannot be considered in isolation.

This study represents an analysis of means of sensing automobile collisions just prior to occurrence. The ultimate goal is to contribute to the development of effective and low-cost dynamic passive restraint systems. In view of the intense effort which has been in progress for some time in examination of impact sensors, and because of the inherent limitations of such sensors for small cars and high-velocity collisions, the TSC program has been explicitly oriented toward investigation of possible means of anticipatory (or predictive) sensing of impending crashes so that more warning is provided. While realization of a completely practical and effective sensor, which would be entirely suitable for mass usage within a few years, would be an especially gratifying result, definition of the program in such a manner would be both unrealistic and misleading; rather, a careful study has been undertaken of the entire problem area.

A first task has been the determination of basic system constraints and required operational characteristics. This has been followed by selection of the more promising techniques for further study, with development of hardware as appropriate and a program of testing and evaluation. Equal importance is being given to development of a basic understanding of the problems, advantages, and technologies involved in anticipatory sensing. The topic of dynamic passive restraints is sufficiently new and complex that it is most important that the Department of Transportation have within it this expertise. Only then will it be possible to evaluate the potential viability and effectiveness of future systems and regulations.

Two related functional tasks have arisen in the course of this program. The first is development of a general capability for characterization of anticipatory sensors. A number of companies outside the automobile industry are interested in this subject, and have indicated interest in TSC's evaluation of their sensors; it is appropriate to undertake an examination of any sensors brought to us for that purpose. At the same time, it is important that TSC not become involved in anything approaching certification. This appears true not only because standards do not exist at present, but also because of the strong interrelationship between sensor, restraint, and vehicle. The only meaningful evaluation must be, as required by NHTSA, based upon vehicle crashworthiness; no element of the system can be separated out for specific approval. On the other hand, it seems appropriate that the expertise developed at TSC be used to provide a characterization of anticipatory sensors based upon analysis of the conceptual approach, study of the actual hardware, and limited field test. A simple examination of this sort should provide a meaningful indication of the promise or lack of promise of a proposed sensor.

Such evaluation is closely related to the second function that has become apparent - the role of interface with technical community. There are many firms, particularly aerospace and electronics, which have considerable skill in relevant technologies and an interest in entry to civilian markets. However, it is important to ensure that their efforts are properly focused, and that they understand the true nature of the problem. In some cases it appears that rather unpromising paths have been followed. It is because of these developing functions of interface and evaluation that some topics in this report are treated at greater length than otherwise might be the case.

1.2 BACKGROUND AND RATIONALE

1.2.1 Collision Dynamics

A measure of the potential effectiveness of passive restraint systems and of the basic requirements on crash sensing is best gained from a brief examination of the dynamics of a frontal collision with a fixed barrier for the strictly one-dimensional case. The treatment here is an extreme simplification of the actual case. It is intended merely to illustrate a basic point, not as the basis for quantitative description of real accidents. The situation is illustrated in Figure 1.1, which shows in simplified symbolic form the circumstances from impact, (a), to when the entire system has come to rest, (c). In the interval T, (Too) between these times, the occupant has traveled a distance and been decelerated from a velocity v_o (initial vehicle velocity) to zero. If the deceleration is uniform and equal to α, these variables are related by this relation.

$$\ell = \frac{v_o^2}{2\alpha}$$

This relation is graphed in Figure 1.2 for various α to suggest the possibilities for passenger protection. v_o here represents the maximum initial velocity for which the occupant can be brought to rest in the stated distance under an acceleration of α. A value of 60G has been suggested as one which is tolerable for properly supported humans. It is seen that an ℓ of three feet permits survival of a 70 mph impact for this ideal case. More realistically the deceleration is far from uniform. This simple calculation only suggests the advantages of dynamic restraints over static; it is difficult to utilize all of the available deceleration distance ℓ, or even a major part of it, with most forms of static restraint, even though a significant portion of ℓ arises from crushing of the front portion of the vehicle.

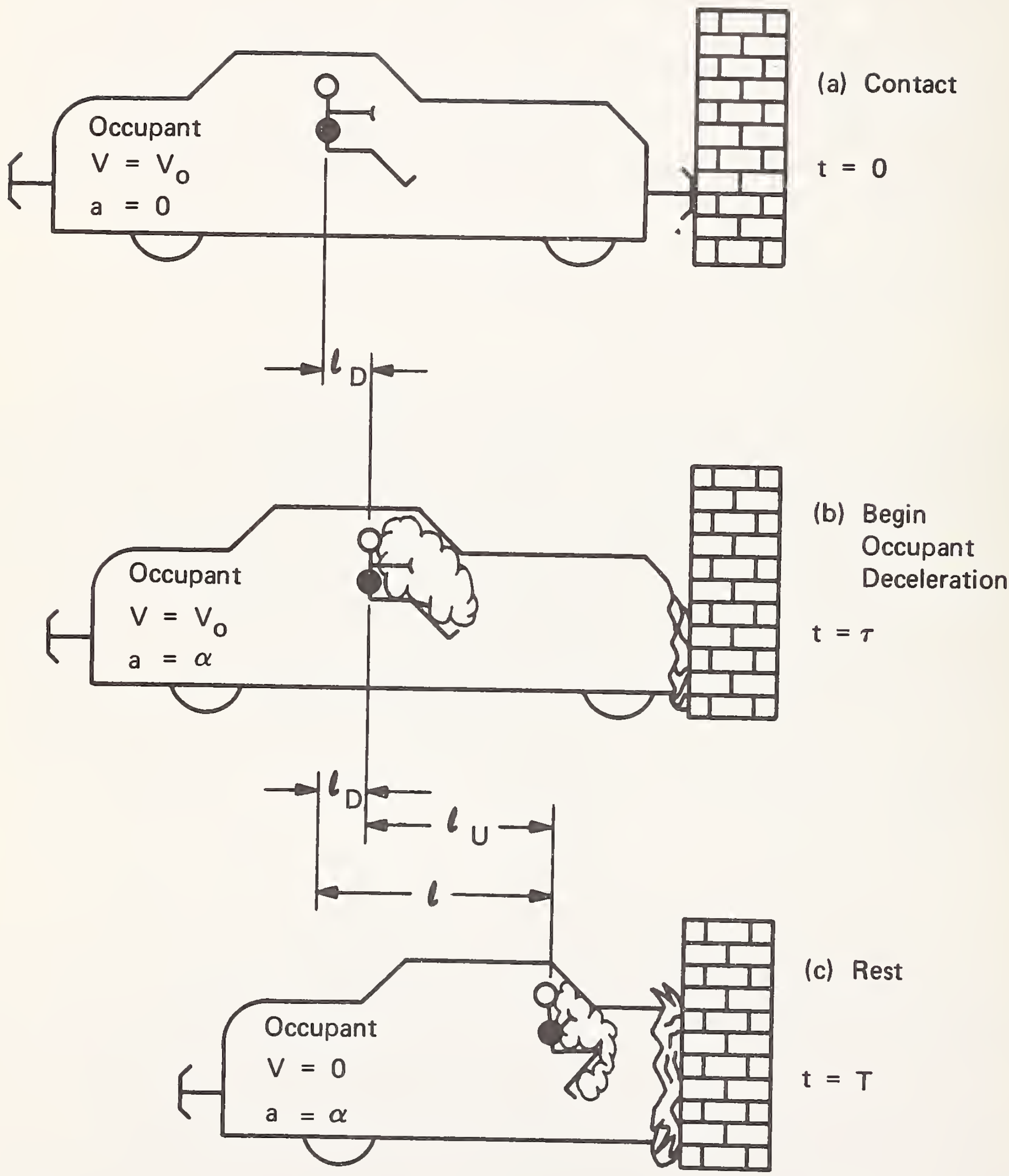


Figure 1.1. - Simplified crash sequence.

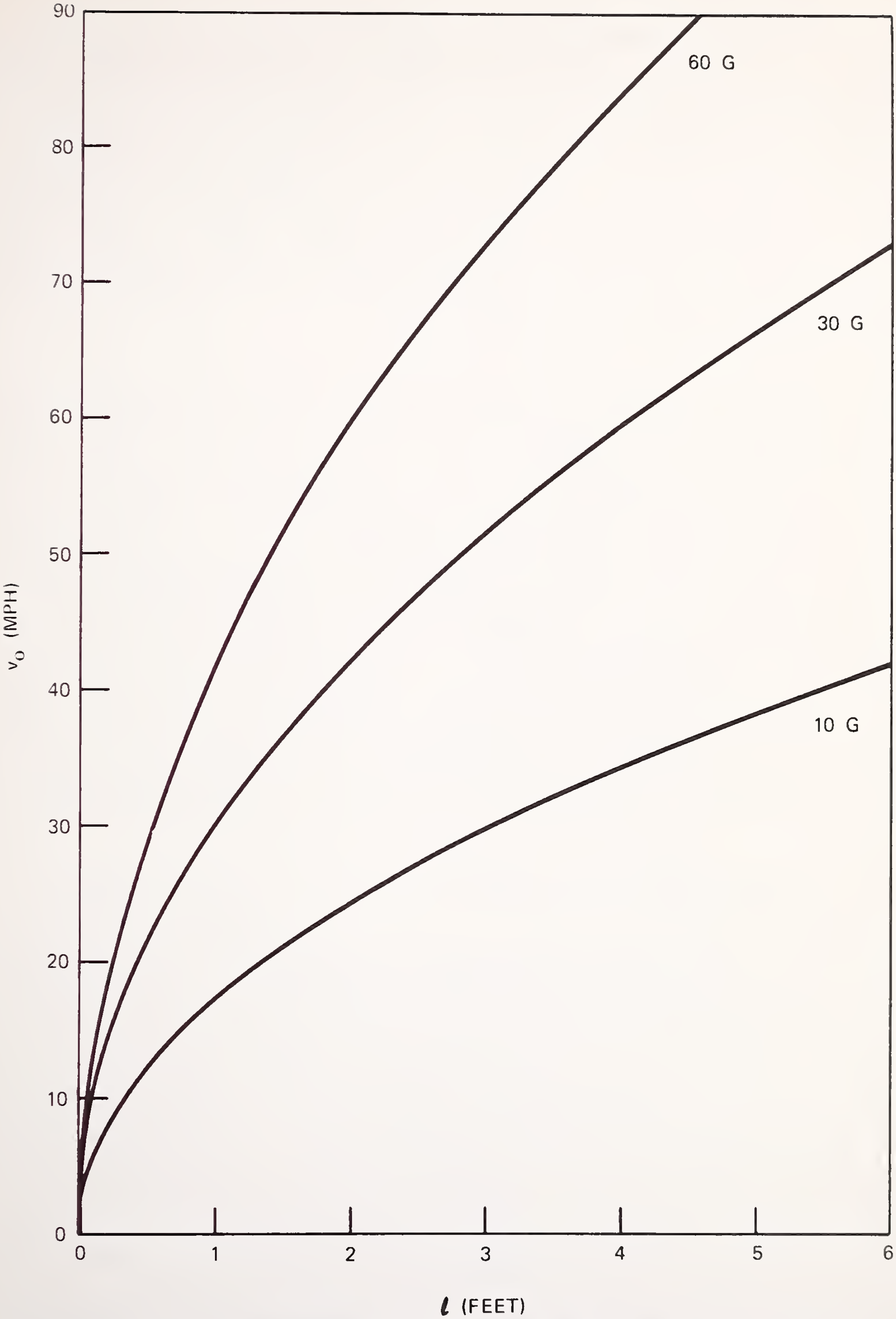


Figure 1.2. - Maximum initial velocity vs. deceleration distance, for various decelerations.

Until the dynamic restraint is fully actuated, the occupant will move forward at speed V_o; so for a total deployment time τ (sensing, actuation, and emplacement) the usable deceleration distance ℓ_U is, $\ell_U = \ell - V_o\tau$, with time taken as zero at the instant of impact. For example, assuming 20G deceleration, with ℓ = 4 feet, τ = 40 msec., the allowable V_o is reduced to 34 mph, compared to 49 mph for the theoretical ideal in which deployment is complete at impact. Note that there is no advantage to completing deployment prior to impact ($\tau<0$), since no occupant deceleration can occur until impact. (Actually forcing the occupant backwards in the vehicle is not considered viable at present).

Figure 1.3 shows the maximum velocity for which occupants can be brought to zero velocity in the indicated distance for specified deceleration, as a function of the delay time between impact and completion of restraint deployment. The benefits of reducing τ to as small a value as possible are clear. But it should further be noted that relatively little advance warning is needed. At 60 mph (1 inch/msec.) activation two feet prior to impact allows τ = 0 for systems which deploy in 24 msec., approximately the value now attainable with inflatable restraints. (The question of required anticipation distance is discussed further in Section 1.3.2). Figure 1.3 should be viewed in the light of values currently considered reasonable: τ of 50 to 60 msec. appears to be a lower limit for air bags with impact sensors, an effective average deceleration of 10 to 20 G is often found (although 60 G would be tolerable if achievable), and ℓ is typically 3 to 5 feet. Further results of such calculations will be found in Appendix A.

1.2.2 Relationship to Current Crash-Sensing Techniques

The means of actuation most commonly used at present is mechanical deceleration sensing. In essence, a mass is constrained by a spring (or other restraining force) such that only a vehicle deceleration of 5 to 10 G will cause sufficient motion to close electrical contacts, triggering deployment. To avoid inadvertent actuation due to minor collisions or road irregularities, mechanical and electrical integration over a significant period of time (tens of msec.) is generally used. In order to respond only to deceleration of the entire vehicle and not to the sometimes violent motions of the smaller elements of the structure, these sensors are typically mounted on the firewall. The total response and integration time associated with such sensors can easily reach 20 to 40 msec., seriously compromising the effectiveness of dynamic restraints, particularly for smaller cars and higher impact velocities.

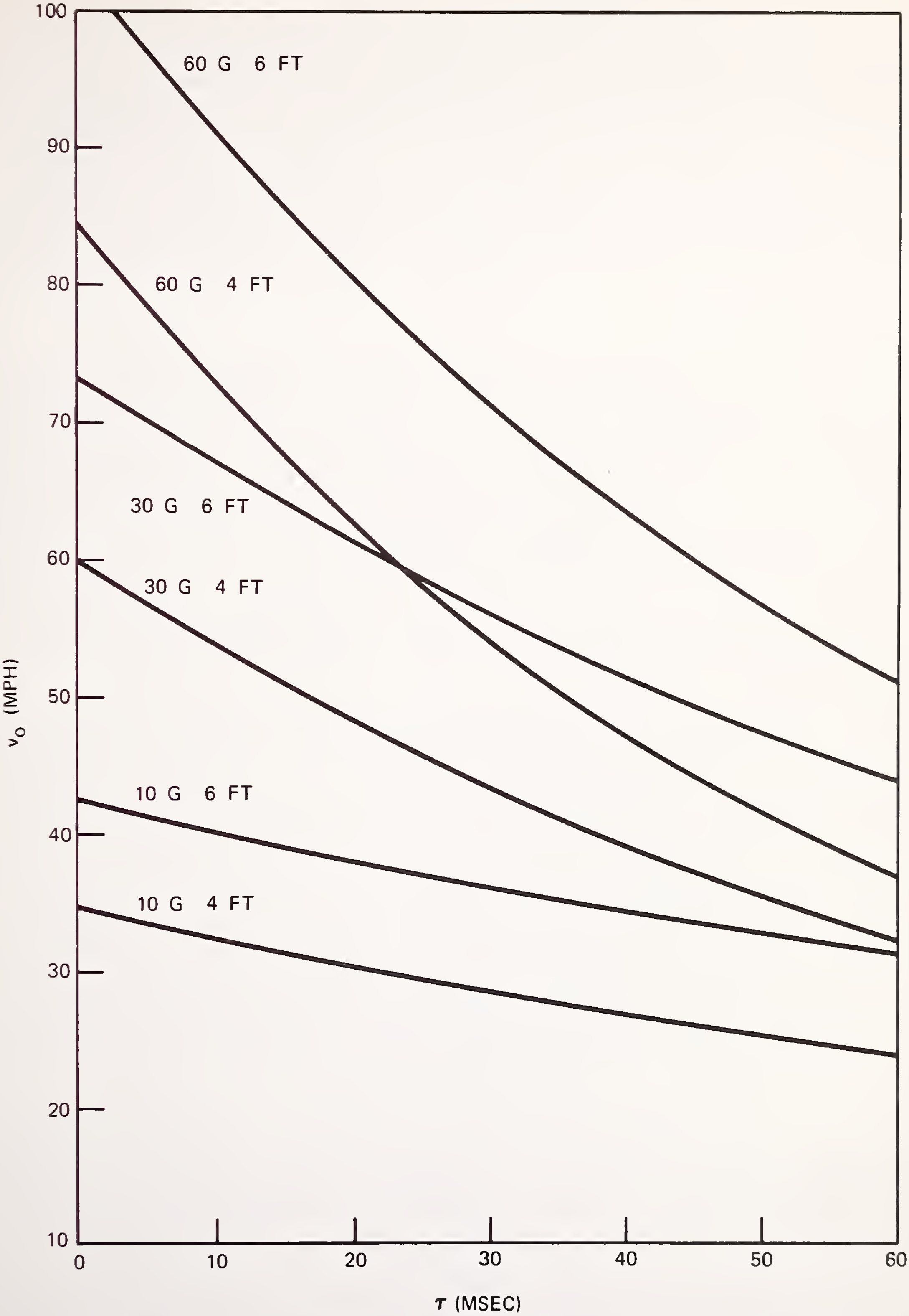


Figure 1.3. - Maximum initial velocity vs. delay time, for various deceleration distance and deceleration.

This is not intended as criticism of methods used to date. The problem is an extremely challenging one, and it remains to be determined whether any truly viable anticipatory system can be developed. Whether overall performance of predictive systems can exceed that of impact sensors is uncertain. However, the results of Section 1.2 do indicate that the potential benefits are well worth serious investigation of possible techniques. This fundamental point is the basic rationale for the TSC program reported herein, the development of experimental anticipatory crash sensors.

1.2.3 Conclusion

The orientation of this program permits a somewhat different approach than that taken by industrial firms, particularly automobile manufacturers. We are not under compulsion to develop a total system suitable for mass production and installation 3 to 4 years from now, meeting standards already specified. We have the freedom to consider a longer time-span. We can consider in greater detail the more basic standards of overall reliability and cost-effectiveness, without being constrained by regulations necessarily prepared in advance of technical realization, and likely to change with time as different engineering constraints or technical possibilities emerge.

The basic operational requirements upon anticipatory sensors will be discussed in Section 1.3. It is sufficient to state here that development of such sensors poses a problem of very considerable difficulty. The complexity of the task become apparent as one considers the great variety of obstacles with which collision is possible, many of which must not induce deployment. These latter include most animals, snowbanks, hedges, most fences and railings, blowing paper or other objects, small stones, curbs, swarms of birds or insects, and large objects of low mass, such as cartons and wooden crates. Even relatively rare occurrences must be considered due to the required near-zero false alarm rate. (Approximately three billion miles are driven daily in the United States; anything that can happen will occur frequently).

On the other hand, real collisions can also involve many different objects: rock, concrete, wood, both living and dead, and metal in many forms. Further, both real and false-alarm targets can occur wet or dry; encrusted in snow, ice, mud, or soot; under conditions of fog, darkness, or brilliant sunlight.

Within such constraints, as well as those of economics and operating environment, it is not obvious that any completely satisfactory system can be devised. However, even a negative

conclusion of sufficient generality would be of value, particularly in determining future safety requirements. On the other hand, the possibility that a workable if not ideal system can be developed with its associated advantages, warrant the effort described in this study.

1.3 BASIC REQUIREMENTS AND CONSTRAINTS TO BE SATISFIED BY ANTICIPATORY SYSTEMS

1.3.1 General Constraints

There are a number of constraints which must be satisfied by any anticipatory crash sensor if it is to be viable in general automotive use. While thorough analysis and considerable development effort may be necessary in some cases to determine whether a particular concept or system is acceptable, it is useful to specify at the outset certain basic requirements which must be met by any practicable approach; they are as follows: (Since almost any system is likely to include electrical and electronic aspects, particular attention is given to factors relevant to them).

a. High Reliability. The average age of automobiles is 5 to 6 years. It is by no means uncommon, particularly in certain regions, to find many vehicles more than 10 years old. Maintainance and periodic inspection are often either very limited or lacking entirely. At the same time, there is approximately a one-in-fifty chance that a given vehicle will be involved in a serious collision in a year interval. Thus, a very low failure rate must be achieved. However, this refers only to the question of failure to operate when needed. As will be indicated later, any failure mode resulting in inadvertent restraint deployment will be a far different and more serious matter. In both categories, the reliability requirements far exceed those normally imposed on automotive systems, and probably represent the most difficult constraints to meet.

   There is another aspect of reliability. Failure of the sensor to actuate restraints because of failure to detect the collision must be rare. That is, it must successfully detect most of the impending crashes for which restraints are likely to be needed, and in a manner that provides substantially greater protection than non-anticipatory sensors. As a target figure, an actuation reliability of 75% to 90% appears to be a reasonable technical goal;

however a rate so far below 100% raises some difficult questions of legal liability. (Section 6.3.2).

b. Freedom from Inadvertent Actuation. This specification is inherently dependent on the restraint system in use. Restraints which can readily and economically be refitted, and for which deployment is neither alarming nor physically hazardous to occupants, may allow a false alarm rate which is fairly high. On the other hand, the attitude of the public toward present inflatable systems suggests that much more rigorous standards will apply until these more ideal restraints can be developed. Some measure of the necessary specification can be gained from observing that a mean time to inadvertent actuation of 100 years, with an automotive population of 100,000,000 vehicles, implies one million such actuations per year, probably quite unacceptable. Since this constraint is related not only to technical considerations, but also depends upon public acceptability and mass psychology, no definite specification can be asserted. However, it is clear that performance of a very high order is required.

c. Insensitivity to Environment. The automotive environment is a very challenging one. Temperatures to which electronic components may be exposed range from -40 F to over +200 F; operation must be relatively unaffected by such variation. High humidity and even frequent water immersion must be anticipated. Ice, snow, grease, oil, mud, and other foreign matter may be expected to accumulate in almost any location. Vibration will often be substantial and occasionally severe. The electrical environment, as well, can pose a severe problem. Depending on the state of the vehicle's electrical system, available operating voltage can fluctuate from approximately 11 to 14 volts. Automobile ignition systems typically generate severe transients, and other electrical and electronic components, each a possible source of interference, are used increasingly in modern cars.

There is also the problem of external electrical noise. Highways often pass close to radio and television transmitting facilities which may be radiating signals of high intensity. Radar signals in the vicinity of airports can also be strong. These are only a few of the many sources of electromagnetic interference now prevalent in our modern

environment. Depending on the nature of the sensor, many other varieties of environmental interference are possible, and a careful study is necessary in each case.

Additionally, the prospect of simultaneous use of many crash sensors of a specific type raises the prospect of inter-vehicle interference, triggering of restraints in one vehicle by some aspect of the sensor in a nearby car. Again, this problem must be analyzed in terms of specific system concepts and realization, and may be a real limitation upon any kind of radiating system.

Finally, the "automobile environment" includes the myriad minor dents and scrapes which most vehicles suffer through low speed collisons and parking. The sensor components must be able to survive such hazards with a low probability of either incapacitation or actuation.

d. <u>Resistance to Vandalism</u>. It is an unhappy fact of modern life that vandalism, malicious mischief occurs quite often under many circumstances. It is possible and perhaps even probable that triggering of dynamic restraints will be seen by many as spectacular, frightening, annoying, and generally non-injurious. These are characteristics which could lead to a substantial vandalism problem should such false triggering be readily accomplished by those so inclined, even if the vandal must exercise considerable ingenuity. Once again, the particular nature of the threat depends on system details, but presentation of a false target - one which the sensor will identify as an incipient serious collision but which in fact should be ignored - is a problem likely to be faced by virtually all anticipatory sensor concepts. A system which met all other criteria but was subject to frequent malicious inadvertent actuations would probably be deemed not viable for that reason alone.

A secondary potential problem is that of damage to to the sensor itself, as often occurs to car radio antennas and windshield wipers. Thus, the sensor must be such that no particularly obvious elements are involved. (This might be thought of as part of the environment problem).

e. Low Cost. Several considerations make low cost a necessity. First, the expense associated with almost any conceivable dynamic restraint system is likely to be a significant percentage of the total vehicle cost, and any substantial addition may exceed the breaking point of both the industry and the public. Further, on a cost-benefit basis, the improvement in performance of anticipatory sensors with respect to impact sensors must be sufficient to warrant the probable additional cost. For example, an added consumer cost of $10 per vehicle represents $100,000,000 per year, and can only be justified if of the order of 1000 additional lives per year are saved. (A figure of $100,000 is often taken as a useful measure of the "value" of human life. A number of approaches may be used to come within a factor of three of this result. While it is often neither feasible nor proper to use such a concept casually, it is of value when one is faced with the task of optimum allocation of a fixed number of dollars. Considering the society as a whole, such a case arises when one has to choose between expenditure on, for example, restraint systems, traffic signals, law enforcement, highway lighting, licensing procedures, periodic inspection, and maintenance. While it is not strictly true that the total resources are fixed, there is obviously a point at which the cost per mile of owning and operating a car will be deemed excessive, and something will have to give. It is likely that the present cost is near that point within a factor of two, and the expense of achieving low-pollution vehicles is going to cause a significant increase). Note that to achieve consumer cost in the range of $10 to $20 requires an extremely low manufacturer's cost, since there is typically a factor of 4 to 5 between the manufacturer's cost and ultimate delivered price.

At the same time, it should be noted that the extremely large production volume associated with the automobile market might provide some help. (A commonly used guideline is that an order of magnitude increase in volume is accompanied by a halving of price. While this is both very approximate and not subject to unlimited extrapolation, it suggests that increasing volume by 10^7 can reduce cost by a factor of 128 compared to that for a single unit). Extensive analysis and prototype development will be necessary to determine whether even the most promising system will have acceptable cost.

1.3.2 Technical Requirements

The above listing of necessary system characteristics provides very general guidelines to overall sensor operation. In addition, it is possible to list certain technical parameters, with the understanding that they not be thought of as rigid specifications, but rather be taken as reasonable starting points, to be modified as necessary to accommodate various kinds of passive restraints and vehicle design.

a. Range. As indicated in Section 1.2.1, actuation approximately 30 msec. prior to impact will permit full deployment of present restraints by impact. At 30 mph this requires 15 inches, and at 60 mph, 30 inches; thus, 2 to 3 feet appears to be adequate. Of course, there are some definite benefits to greater warning. Slower restraint deployment can reduce noise and other hazards, and would increase the degree to which oddly positioned occupants could be accommodated. On the other hand, greater anticipation distance raises the problem of near misses. Considerable variation of trajectory can occur in the last 10 to 20 feet before collision, particularly if the target object is also a moving vehicle. For example, consider the case of two cars approaching each other at equal velocity, both with perfect brakes ($\alpha = -1.0$ G). If both cars apply full braking power at 15 feet separation with initial closing velocity of 30 mph, they will not collide. For an initial closing speed of 24 mph, impact is avoided if full braking is instituted when the vehicles are only ten feet apart.

   Thus, a sensor which attempts to detect impending collisions at such distances must inevitably fail by producing an inadvertent actuation, in a case such as described above, and will be greatly challenged by a wide variety of situations in which accidents are narrowly averted through evasive maneuvers. Even a fairly sophisticated system for sensing target size, shape, position, velocity, and acceleration, and capable of trajectory prediction, will have a difficult task; development of such a sensor, to say nothing of manufacturing within reasonable cost constraints seems almost unthinkable. Finally, the technical characteristics of various particular schemes may militate against any attempt to achieve large anticipation distances. (For example, see Section 3.4.3).

b. Sensing Region. The preceding consideration can be generalized to the question of sensing volume, rather than distance alone. This is closely tied to the nature of the restraints. If no protection is provided in side collisions or rollovers, there is no benefit to sensing them. Moreover, the greater the attempt to sense in other regions than directly ahead of the vehicle, the more difficult the task of eliminating false targets and near-miss situations. On the other hand many collisions which are not purely frontal still have major forward deceleration components for which deployment is appropriate. Restraint effectiveness is enhanced to the degree that such collisions are anticipated. As with many other aspects, this question must be resolved separately for each sensing concept, in the context of actual accident statistics. (The present NHTSA regulations require basic crashworthiness for impacts $\pm 30^{\circ}$ from frontal; this seems a reasonable general value).

Additionally, there is the question of vertical range. It is desirable to ignore low obstacles, such as curbs, small ditches, and railroad tracks. At the same time, some large truck bodies overhand the chassis by several feet at a significant height, and an effective sensor should detect such obstacles. A sensing region reaching vertically from approximately 1 to five feet elevation should be nearly optimal.

c. Velocity. The minimum closing rate for which activation should occur is partially a function of vehicle size, static restraints, etc. It would be desirable also to make this parameter dependent on the nature of the target, but this is probably not feasible. It is a difficult task (perhaps impossible within the indicated constraints) to devise a sensor with satisfactory target discrimination. To attempt to go beyond that is worth consideration but unlikely to be fruitful.

The more important consideration here is to avoid certain types of inadvertent actuations, those associated minor collisions, traffic congestion, parking, etc. Thus, a simple and probably effective approach is to set a threshold speed below which actuation is not permitted. Values typically suggested are 10 to 15 mph.

Note that this raises the question of relative versus absolute velocity. Since the energy interchange in any collision is determined by relative velocity (closing rate), this seems by far the more desirable approach. Consider the case of a vehicle with a speed of 60 mph colliding from the rear with another travelling at 55 mph in the same direction. Deployment is neither necessary nor desirable. Further, if one wishes to use vehicle velocity (ground speed) as a control input, there is a definite instrumentation problem. Collisions can occur under a great variety of circumstances: wheels locked, engine stalled, etc; no simple means is apparent for utilizing speedometer or similar information. (This is not to say that there are not definite advantages to rendering any system inoperative for very low vehicle velocities. Whether this warrants the added complexity and cost depends on the particular sensor).

There is no upper velocity limit for sensor operation, but proposed crashworthiness regulations require effective triggering to at least 30 mph (barrier crash), equivalent (in some senses) to a 60 mph closing rate with a vehicle of similar size. Effectiveness at higher speeds would be beneficial, and will almost certainly ultimately be required (to the degree that technology permits) up to possibly 50 to 70 mph for barrier crashes.

Since system complexity is likely to be related to the span of velocities over which the system must operate, it is desirable to limit response to a maximum of 150 to 160 mph. Such limitation should help in various respects such as noise, false alarms, and inter-vehicle interference.

Finally, it may be feasible to relate anticipation directly to velocity, so that the time interval τ (Section 1.2.1) used is varied for optimum results. For example, a sensing distance of three feet provides approximately 36 msec. for deployment at 60 mph (about the right amount). But over 100 msec. is provided at 20 mph, leading to deployment 70 msec. in advance of impact; this is not optimal. Sensors which inherently determine velocity, such as doppler systems, may permit necessary adjustments with a minimum of additional signal processing.

With particular reference to doppler systems, it should be noted that it is not necessary to design

a system which distinguishes between the doppler shift of approaching and receding objects (increase or decrease of original frequency). It is rare when a large object is found two to three feet in front of an automobile, travelling away from it with a velocity greater than 15 mph. (This would imply acceleration of well over 2 G).

d. Response to Various Targets. This topic will be treated for specific approaches in succeeding sections, as appropriate. The basic goal is to respond to the mass or immobility of target objects. While this aim cannot be achieved perfectly in general, the degree to which it is approached provides a useful criterion for consideration of various sensor systems. The context, of course, is that of normal automotive usage: statistics provide some guide. For example, slightly under one-half of target objects in automobile accidents are other vehicles. Similarly, abutments, trees, and standard roadside structures represent objects that it is desirable to be able to detect. Indeed, a detailed study of the relative importance in both numbers and accident severity is useful to the evaluation of suitable sensing techniques. However, as will be seen in following sections, the number of potentially viable concepts is so limited, that beyond determination of reasonable likelihood of effective operation, this subject does not appear to be an appropriate precursor to an investigation of potential sensing methods; rather it should be a part of the final analysis of system effectiveness.

It is frequently suggested that certain techniques, such as radar could be made more effective if common objects were equipped with either special reflectors or absorbers so that they are more easily identified as either threatening or non-hazardous. While such actions might be beneficial to enhance the effectiveness of any system which has already been found acceptable, it would be a courageous suggestion indeed that the entire highway environment be so coded simply to make a particular anticipatory sensor viable. (It is likely that such an avenue would be blocked on simple cost-effectiveness grounds, to say nothing of practical and political difficulties).

SECTION 2
POSSIBLE TECHNIQUES FOR ANTICIPATORY SENSING

2.1 INTRODUCTION

There are many known or conceivable means of sensing the presence, closing rate, and nature of nearby physical objects. The inherent characteristics of each technique must be evaluated in terms of the wide variety of targets and environmental conditions which can occur, as well as in the light of the guidelines suggested in Section 1.3. Most methods can be discarded immediately as far as this application is concerned, and there will be no attempt made here to document the failings of those obviously unsuitable. Nor should this treatment be considered definitive; it is possible that innovative scientists and engineers can devise effective sensors by means not mentioned, or utilizing techniques considered here and discarded. However, a practical investigation is necessarily based on choice of the most promising starting point, and a brief but careful survey appears to suffice in this case. Indeed, the real burden is to illustrate that any truly promising methods can be found.

The basic classifications of sensors used here are mechanical, proximity and ranging Mechanical methods include the use of probes, extendable bumpers, etc. Proximity techniques are here defined as those which are inherently static, such as capacitive, inductive, magnetic, and radiometric. In ranging sensor systems, as the term will be used here, energy in some form is radiated ahead of the automobile and the reflection (if any) is analyzed by an appropriate detection system to provide information such as range, movement, and size of the reflecting object. All three classes will now be discussed briefly.

2.2 MECHANICAL TECHNIQUES

Direct mechanical sensing has many advantages. The inertial response of a vehicle in the first stages of a collision gives good discrimination of object mass. False alarms can be virtually eliminated, and properly designed mechanical sensors have little sensitivity to environment. They can be inexpensive and their operation can be independent of the surface features and composition of targets. As mentioned previously, mechanical sensors are limited in effectiveness by slow response speed; the collision must start before it can be sensed. Only limited improvement in this respect appears feasible.

There are a number of advanced mechanical techniques that could be explored. The use of a bumper-type probe, suitably styled, that is automatically extended in front of the moving vehicle and retracted at low speeds is one possibility. Undoubtedly a number of innovations are under consideration currently as successors to present mechanical sensors. Further examination of such systems is appropriate, and will be discussed in Section 3.2.

2.3 PROXIMITY SYSTEMS

Proximity detection techniques are commonly used in many applications. Inductive and magnetic vehicle detection is widespread. However, the apparently inherent flaw in such approaches is the dissimilarity between possible targets. Further, in the unconstrained environment of automobile use, it is difficult, and often impossible to distinguish by such means between effects of range, velocity, and size. Also, electrical techniques (capacitive and inductive) would require physically large sensing structures, which are to prove inconvenient. Another possible proximity detection technique is infrared radiometric sensing. However, this method will probably be far too vulnerable to environment, and is unlikely to be distinguish well between hazardous and innocuous obstacles. In summary, proximity techniques do not appear sufficiently promising to warrant further investigation at TSC.

2.4 RANGING SYSTEMS

2.4.1 Optical Techniques

The ease of focusing the transmitted beam and reflected signal at optical wavelengths makes possible excellent discrimination of target position. If a number of transmitted beam paths are used, target dimensions can be measured directly. The closing velocity can be determined from doppler shift or from the rate of change of pulse echo time. At optical frequencies both can be extremely accurate.

An optical system is seriously degraded by dirty apertures, and by dust, fog, or snow in the air. The aperture problem is perhaps not insoluble. But more important, false alarms with an optical system would be extremely difficult to eliminate, due to the fact that heavy snow or fog, or a highly reflective object of low mass, such as a large piece of paper or soft pile of snow, could readily trigger the system. This factor could also represent a substantial vandalism problem.

Although optical equipment possibly could be inexpensive and highly reliable in itself, the environmental sensitivity and susceptability to inadvertent actuation renders optical techniques unsuitable for intensive investigation, regardless of other virtues.

2.4.2 Radio Techniques (Radar)

Radar has been developed and used extensively for over 30 years for object detection, most commonly in aviation and marine applications. The basic concept is indicated in Section 2.1; radio frequency energy is radiated by an antenna, then reflected or scattered by various objects, and received by an antenna that can be the same one used for transmitting. The frequency, transit time, amplitude, phase, azimuth, elevation, and polarization of the received signal all can provide information about the reflecting object and its motion relative to the radar system. In particular, by virtue of the familiar doppler effect, the frequency of the reflected signal will differ from that of the transmitted signal by an amount directly proportional to the relative velocity of radar unit and reflecting object. It is electronically simple to mix the received and transmitted energy to obtain an output at the doppler frequency, thus permitting very simple velocity measurement. This technique is called homodyne detection. It is the principle on which police speed-monitoring radar systems operate.

Radar systems can be realized with state-of-the-art components in the frequency range from less than one GHz to tens of GHz (1 GHz = 10^9 Hz). As a general rule, antennas must be of the order of one wavelength wide at the frequency used. For significant directivity, they must be substantially larger. This consideration alone suggests use of a wavelength well under one meter, or a frequency above 300-MHz. Also, targets significantly smaller than one wavelength in linear dimension will not give a useful return.

Another point favoring use of higher frequencies is wider available frequency allocations and reduced commercial use——important considerations in avoiding interference.

Further guidance on choice of frequency can be obtained from consideration of available microwave sources. At lower radar frequencies transistor oscillators or transistor-varactor circuits are feasible. However, both represent significant cost and complexity. On the other hand, recent developments in solid state microwave technology (described in Section 3.4.1)

suggest the desirability of somewhat higher frequencies. These devices operate particularly well in the range from 10 to 20 GHz, which also permits antennas of convenient size (with apertures of several inches in size).

Still higher frequencies would increase cost substantially, as both oscillatory diodes and other components require much closer tolerances in manufacturing; commercial and military markets, and hence production volumes, are also much smaller at these higher frequencies. Thus, it appears that the optimum form of ranging system will be microwave radar, in the X-band to K-band range.

Whereas range and range rate can be determined directly, the size of the target can generally at best be inferred from the magnitude of the returned signal. One can expect only limited correlation between target mass and measured cross section. Electromagnetic reflectivity is determined by dielectric constant and conductivity. Therefore, reflections from birds, metal cans, scraps of metal foil, sewer gratings, and metal roadways on bridges would compete with returns from dangerous objects such as vehicles, stone walls, trees, and dry embankments.

Also, because of the high speed of propagation of the signals employed and the short distances involved, the response time of the associated circuitry must be extremely small. For a target one meter from the antenna, the reflected signal returns in 6/7-nanoseconds. To derive accurate range and closing rate information for such return times, resolution of a fraction of a nanosecond is necessary if conventional circuits are used; this performance would undoubtedly have sharp and unfortunate impact on cost. Thus, innovative system design will be required to develop a viable microwave sensor.

Pulse techniques offer both advantages and disadvantages. Gating and coding circuits may permit good distance discrimination and high immunity to noise and interference from other vehicles. On the other hand, complexity and cost is likely to be greater, and antenna size and location may present problems. The viability of such methods is highly dependent on the particular realization considered, but they appear less promising than cw radar.

In summary, microwave radar, while not without serious drawbacks, has in its favor a wealth of well-known techniques and components, and on balance is sufficiently promising to warrant detailed investigation.

2.4.3 Acoustic Techniques (Sonar)

The extensive use of sound waves for communication and target detection both in the biological realm and in manmade devices suggests the possible value of an acoustic crash sensor. In underwater applications (fish location, submarine sonar, depth measurement) low frequencies are most often used because of the low attenuation and greater range possible. For an air-medium high resolution system, as the present case, relatively short wavelengths are required - significantly less than one meter; - avoidance of creation of audible noise, as well as low susceptibility to noise, imply frequencies above the audible range: i.e., above 20 kHz. Frequencies above several hundred kHz suffer extreme attenuation in air under certain conditions, and so are unsuitable. Thus, the approximate range of 30 to 100 kHz appears to be the optimum location for an acoustic crash sensor. These are the frequencies used, for example, for sonar aids to the blind.

In the crash sensing application, acoustic ranging or sonar systems have some favorable features. The low propagation velocity permits modulation and signal processing at frequencies approximately one million times lower than for electromagnetic radiation. The reflection time for an acoustic signal from a target at one meter is approximately 6 ms. For simple doppler systems the maximum allowable wavelength for an uncertain ΔR in range and Δv in velocity is given by:

$$\lambda = 4\,\Delta R \cdot \Delta v/V$$

where V is the carrier velocity and v the vehicle velocity.*
A wavelength λ = 1 cm., corresponding to a frequency of 33 kHz., is allowable in an acoustic system permitting ΔR = 0.1 m. and Δv = 1 m/sec.
(For electromagnetic radiation the same calculation yields a maximum allowable wavelength of 13Å.)

In addition, acoustic reflectivity is a function of density and bulk modulus. Therefore, there might be better correlation between mass and echo intensity than there is in the case of electromagnetic signals. Acoustic attenuation in air is much greater than microwave attenuation, and this fact should help limit interference between autos. Because of the longer wave-lengths employed, rain, falling snow, and dust should have less effect on operation of an acoustic system than they would have on an optical system. A specially cleaned

window could reduce the effects of the vulnerability of the transducer or antenna apertures to ice, snow, or mud although general environmental problems such as noise, wind, road debris, or weather are likely to represent the most challenging aspect of system design. This method appears worthy of further analysis and investigation.

SECTION 3
DETAILED ANALYSIS OF SELECTED TECHNIQUES

3.1 INTRODUCTION

Sections 1 and 2 outlined the basic requirements of anticipatory sensors, and indicated some of the difficulties faced in attempting to realize such a system. A number of possible methods have been described, with the conclusion that only three seemed appropriate for further consideration at TSC, taking into account the size of the effort. The three selected were (1) advanced mechanical sensors, (2) microwave radar techniques, and (3) ultrasonic (sonar) systems. A more detailed analysis of these methods follows.

3.2 MECHANICAL SENSORS

To obtain advance warning with a mechanical sensor, one must, in essence, advance the physical position of the sensor relative to the automobile. There are a number of difficulties associated with this approach. The key problem with most anticipatory sensing concepts is avoidance of false alarms from the many and varied obstacles or objects a car might conceivably strike. An indication of the mass (or immobility) of such a target is necessary in order to predict the seriousness of the collision, and thus determine whether restraint system deployment is warranted. While a mechanical system offers this capability directly, the sensitivity of this method depends on the capacity of the sensing system to absorb energy. For currently conceived sensors, the sensing system essentially consists of a firewall-mounted accelerometer plus the entire front section of the automobile. If the accelerometer is to register a sustained five-G deceleration, a large amount of energy must be transmitted by the quite massive forward assembly so that an unequivocal crash indication is obtained. On the other hand, a physically small sensor extended in front of the car might undergo severe decelerations even for relatively small impacts. Further, such a sensor protruding from the vehicle would be a safety hazard in its own right, even if withdrawn at low speeds. Finally, a mechanism which could extend and retract a reasonably massive wide sensor structure, cycle reliably every time the car passes a set speed, and operate for perhaps ten years without maintenance or failure, would be very difficult to produce at an acceptable price, even in very large quantities. To obtain real benefit, the extension would have to be substantial. At 60 mph, allowing 10-msec for sensing and triggering, and further assuming a 30-msec crush time for the vehicle engine compartment, the sensor would have to impact the target 3 to 4 feet in front of the car.

This is not to say that advanced warning cannot be obtained mechanically. Two aspects of automotive development may contribute to the utility of this method. First, as the design of the forward sections of automobiles are improved with respect to energy absorption, a small but significant decrease may be achieved in the degree of impact anticipation required. Of greater significance is the potential development of extendable, energy-absorbing bumper structures. The principle motivation for such development is energy absorption to minimize damage to the vehicle at low speeds, or to the occupants at higher velocity. However, these characteristics should make it well suited to sensing impact in a manner appropriate for triggering of restraint systems.

Since the viability of a mechanical crash sensor depends so heavily on these other developments currently outside the purview of TSC, further investigation of this concept has been suspended.

3.3 GUIDELINE FOR ANALYSIS OF RANGING SYSTEMS

Before discussing the microwave and ultrasonic radar systems in detail, it is appropriate to examine inherent characteristics of these different modes. Points which must be included in any serious investigation include:

a. <u>Signal Strength</u>

1. source
2. transmitting transducer
3. path loss
4. target characteristics
5. receiving transducer
6. receiver

b. <u>Environment</u>

1. variability of propagation
2. weather protection
3. noise spectrum
4. vandalism

c. <u>Overall System Aspects</u>

1. inter-vehicle interference
2. radiation hazards
3. cost
4. effectiveness

    (a) "True" collisions
    (b) "False alarms"

While some of these points require further investigation or evaluation, all can be discussed to some degree for both types of ranging sensors. Cost factors, item c.3., will be discussed under other headings also, as relevant.

3.4 MICROWAVE RADAR CRASH SENSORS

3.4.1 Signal Strength

a. Source. Microwave solid state sources have been the subject of intensive investigation, principally sponsored by NASA and DOD, for a number of years. Two types of oscillatory diodes have been realized in practical form, both providing direct conversion from dc to microwave power with no additional circuit elements beyond the diode and its mounting. The avalanche, or IMPATT (Impact Ionization-Avalanche-Transit Time) junction diode is somewhat more highly developed and more efficient than the Gunn (transferred electron bulk-effect) diode, but requires approximately 80 volts for a 10-GHz diode, compared to the convenient 12 vdc for the latter. Costs and reliability are about equal. Either could be used in an automotive system, but the necessity of compatibility with battery operation, initially favors the Gunn device. (Use of the IMPATT would require a dc to dc inverter circuit, and a slight but possibly significant increase in cost. Diode cost and reliability will ultimately determine the choice.) While these devices are currently quite expensive, one manufacturer has publicly announced plans to market Gunn diodes at $5 each in lots of 100,000. The history of the semiconductor industry, and its economic dynamics, are such that one can quite confidently predict even lower prices should a large-volume market develop. (Transistors, for example, once very expensive, now often sell for a few cents in unit quantities, and a fraction of a cent in large volume.)

   Power output of 100 mW is easily obtained, and is more than is necessary for this application. Reliability is estimated to be greater than 40,000 hours mean operating time before failure. This estimate largely represents the limited time such tests have been underway, 100,000 hours is quite possible.

b. Transmitting Antenna. Two types of antennas seem appropriate to this application. One, the familiar horn type, could easily be cast, molded, etc. It seems unlikely that such a simple unit could cost significantly more than the material from which it is

fabricated when used in automotive quantities. An alternative, not yet developed for civilian use, is the slot array using a stripline feed. This antenna is fabricated in the form of laminated layers of metal sheets and dielectric. It would be more compact and should be even less expensive in high volume. It also offers somewhat greater ease of controlling antenna pattern. Both types have bandwidths of at least tens of megahertz.

c. Path Loss. Air, even under extreme weather conditions, has negligible microwave attenuation for such applications. At 10 GHz, in cloudburst-intensity rain, attenuation may reach 20 dB/kilometer, or .02 dB/meter.

d. Target Characteristics. Targets can be of wide variety, both reflective and scattering. The waves will be reflected or scattered by obstacles or portions of obstacles comparable in size to a wavelength -- 3 cm at 10 GHz.

Generally, good reflection will depend on the dielectric properties and conductivity of the target surface. Hence, there should be substantial reflection and scattering from motor vehicles, no matter what the aspect. Dry telephone poles, on the other hand, may give a small return, and large wet animals could reflect quite well. Concrete, brick, and stone should be good reflectors.

e. Receiving Antenna. Microwave antennas are typically of wide bandwidth and highly efficient. Receiving and transmitting antennas can be identical if desired.

f. Receiver. For reasonably simple signal processing, as is envisioned, a very few components -- diodes, integrated circuits, etc. -- are needed. Cost, in high volume, can be very low, with no compromise in reliability.

3.4.2 Environment

a. Variability of Propagation. As indicated above, microwave propagation over such short distances is essentially unaffected by temperature, humidity, or precipitation.

b. Weather Protection. Due to widespread usage of microwave communication systems, the state-of-the-art in weather proofing is highly advanced. In addition, the transparency of many materials to electromagnetic radiation makes this a relatively easy problem.

Antenna covers ("windows") with appropriate dielectric constant and conductivity have very little effect on transmission, and cost very little for small antennas.

c. Noise. Both man-made and natural background noise are reasonably low in the microwave range. It should be possible to design a practical crash sensing system that is activated only by signals much stronger than prevailing noise levels. Police speed-measuring radar could be a problem, although it is probable that received signal strength will be sufficiently low to avoid difficulty. Additionally, the considerations listed under part 3.a., Inter-vehicle Interference, will provide a margin. If necessary, the system could simply avoid use of police-radar frequencies.

d. Vandalism. The principal concern here is with maliciously induced restraint deployment. As indicated in Section 3.4.3.a., a false microwave signal would be very unlikely to fall in the passband of the receiver. (Even a swept frequency system would be unlikely to fall in the passband sufficiently long to induce triggering.) This, coupled with the absence of microwave sources from the public market, there should prevent serious problems from extraneous signals.

The far greater difficulty lies with creation of false targets. This is closely related to the general false-alarm problem, and the same treatment serves for both. Basically, this must consist of use of a high triggering threshold. For example, the system should not trigger for any target, no matter how high its reflectivity, which has a physical area of less than one square foot. With this requirement, it is unlikely that many such objects can be thrown successfully. There is, however, the additional problem that otherwise harmless obstacles might be placed in the road and cause deployment. This could turn out to be either a serious problem or a very minor one; further system development is necessary for such a determination.

While a crash sensor could be rendered inoperable by vandalism to the car, the antennas should be readily integrated into the design -- they need be only 3 to 5 inches in diameter -- and should not attract atten-

tion. The weather-proofing shields can be extremely durable. Finally, there should be very little satisfaction to such vandalism; immediate breakage could be barely noticeable, and failure of the system would be exceedingly unlikely to occur in the presence of the miscreant.

3.4.3 Overall System Aspects

a. Inter-vehicle Interference. Analysis of this aspect requires an estimate of system bandwidth. While sophisticated systems could have very substantial requirements, there is a basic minimum. A simple continuous wave (cw) technique requires at the very least that the receiver be able to accept a frequency f_r equal to the transmitted frequency f_o plus any foreseeable doppler shift f_d:

$$f_r = f_o + f_d$$

In general, $f_d = 89.6 \times v_{mph}/\lambda_{cm}$,

where v_{mph} is the closing rate in miles-per-hour, and λ_{cm} is the wavelength of the radiated signal in centimeters. (These mixed units are convenient in this application.)

Since $f_o = c/\lambda_{cm}$, with c the propagation velocity in cm/sec.,

$$f_d = [89.6 \times f_o/c]\ v_{mph}, \text{ or}$$

$$\frac{f_d}{f_o} = \frac{89.6}{c} v_{mph} = .3 \times 10^{-8} \times v_{mph}.$$

To allow for closing rates of up to 160-mph, the maximum f_d/f_o which the system must accept is

$$\frac{f_d}{f_o} = .5 \times 10^{-6}$$

This not only establishes the extremely narrow-band nature of the system, but also shows that for f_o = 10 GHz, the maximum f_o = 5000 Hz. Thus, if a .5 GHz band is available for crash sensors, centered near 10 GHz, 100,000 transmitters could coexist with no interference. Probability theory shows that a specific car could be brought into close frontal contact with 69,000 other radar-equipped vehicles, with a 0.5 prob-

ability of at least one inadvertent triggering. Expansion to a 2-GHz band, and reduction to 100-mph (and lower) closing rates would increase this to over 346,000 exposures to other crash-sensor transmitters before a 0.5 probability was reached. If the transmitting antenna is on the left side of all vehicles, this should greatly reduce the number of such exposures, since all autos will radiate their microwave beam toward the roadside. Remaining occurrences typically would involve cars at right angles, as in intersections. If the system were inoperative at extremely low vehicle velocity, this problem would be further relieved. Only actual tests can show how close two vehicles would have to be to bring about triggering, but the broad antenna patterns typically used should provide enough spreading loss after a fairly moderate distance.

This is clearly a problem area so far as widespread use of a microwave system is concerned. On the other hand, the above discussion is intended to indicate that it should not be an insurmountable one, simply on a statistical basis. Beyond that, one could go to coding schemes in which a given receiver can "recognize" signals of that vehicle's transmitter. Such a procedure would be very likely to add substantially to system cost, but might be necessary. It is clear, however, that both the Department of Transportation and the FCC will find it necessary to monitor very closely all automotive use of microwave systems, whatever their function, to avoid disastrous interference problems.

b. Radiation Hazards. For antennas of modest directivity, as planned for the sensor, with a 100 mW oscillator, power density at the antenna is approximately 1 mW/cm^2, an acceptable level. (The present voluntary U.S. standard is 10 mW/cm^2, averaged over any six-minute period. Current HEW requirements for microwave ovens, recently made more stringent, permit 1 mW/cm^2 new; 5 mW/cm^2 over the life of the unit. FCC limits on intrusion alarm systems are of this order.) An operating system may well require substantially less power than the 100 mW indicated, so that a radiated power density of .1 mW/cm^2 is feasible. Again, if the system is inoperative at zero and very low speeds, individual exposure can be very low. This, too, highlights another aspect of microwave automotive systems; DOT, FCC, and HEW must keep careful watch over this possible dramatic increase in spectrum usage and total microwave radiation.

c. Cost. Cost factors were considered to some degree in Section 1; at present, it appears that a microwave sensor system could be produced for \$10-\$20. However, solution of some of the possible problem areas indicated (or others as yet hidden) could bring about a drastic increase.

d. Effectiveness. The ultimate system effectiveness of a microwave crash sensor cannot yet be determined. Nearly half of the fatal collisions involve impact with another vehicle, which will presumably be a good radar target. The distribution of other targets, and evaluation of system effectiveness for them, awaits both experimental tests and further study of accident statistics. (Verification of the radar characteristics of automobiles is also needed.)

   Rejection of virtually all false alarms remains a difficult problem, but should be possible by imposing a sufficiently restrictive test for triggering, such as a high amplitude threshold for the reflected signal. On the other hand, this will reduce the probability of deployment in a "true" collision. Again, experimental data is required.

   The maximum target distance at which such a technique can operate is still to be determined. As pointed out in Section 1.2.1, only short distances are required. Use of a high triggering threshold, for example, will probably restrict successful sensing to a maximum distance of four to six feet, and the optimum is probably somewhat less. (While many types of radar systems could function for far greater ranges, such operation will almost certainly be accompanied by an unacceptable false alarm rate and increased inter-vehicle interference. Note that the intensity of signals received from transmitters located on other vehicles will be reduced by a factor proportional to the square of the separation distance; whereas reflected (radar) signals decrease with the fourth power of range. Thus, doubling the radar sensing-distance, by decreasing the threshold, increases by four times the range at which inter-vehicle interference will be a problem, and also greatly enhances the likeihood of low reflectivity "false alarm" targets giving a return above threshold when close to the vehicle.)

   One particularly important conclusion which has been reached concerning microwave crash sensors is that a system utilizing only a single antenna has a severe inherent problem. When even a very small target, such

as a beer can, comes very close to the antenna, the reflection will be as strong as for a large real target much further away. Quite sophisticated circuitry is necessary to obtain range information adequate for rejection of false targets close to the aperature.

On the other hand, this difficulty cannot arise with two or more antennas, since the small object has to be reasonably far from one antenna or the other, and this will either receive little power to reflect, or will reflect only a small amount into the receiver. This is illustrated in Figure 3.1. Such a system, with separate transmitting and receiving antennas some distance apart, is called a bistatic radar system.

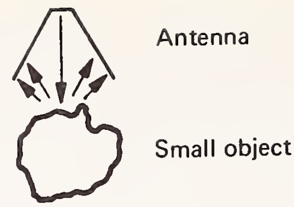
3.5 ULTRASONIC SONAR CRASH SENSORS

3.5.1 Signal Strength

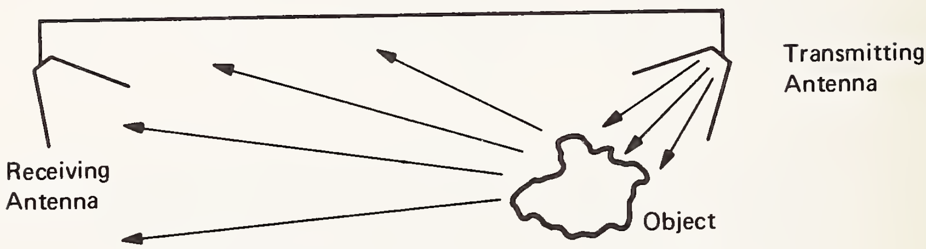
a. Source. There should be no difficulty in design of a reliable, low-cost transistor oscillator using integrated circuits. Consumed power should be of the order of watts at most, and should be easily supplied by an automobile electrical system.

b. Transmitting Transducer. For a cw (continuous wave) system, a narrow-band transmitting transducer is sufficient, provided that the oscillator is adequately stable. Reasonable efficiency is desirable, to minimize the power required from the oscillator circuit. For a system involving sophisticated modulation -- coding, chirp, etc.—bandwidth could be a problem, as indicated in 3.5.1.e. Radiation pattern should be readily tailored to the desired shape.

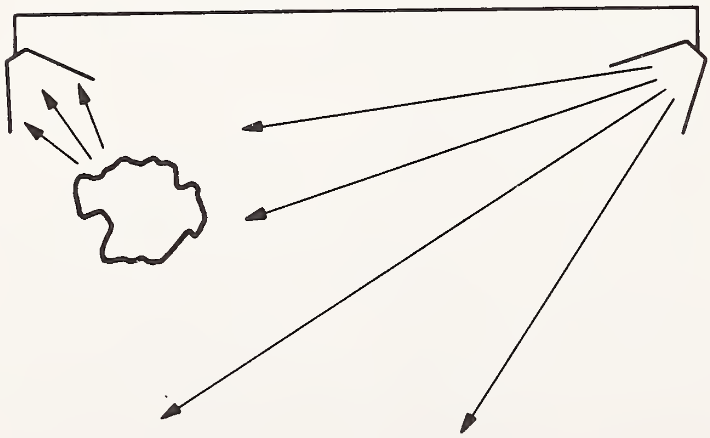
c. Path Loss. Atmospheric attenuation of acoustic waves is strongly dependent on temperature, humidity, and frequency. Under the best conditions, even at 100 KHz, the loss can be under .1 dB/meter, which would be negligible in this application. However, the worst case can reach 10 dB/meter, or for a total path length of 3 meters, 30 dB loss. (This is for 100 KHz; attenuation is proportional to the square of the frequency.) While loss of this magnitude can be made acceptable through use of increased transmitter power, the consequences of variation from low to very high attenuation due to changes in environment are far more serious. These are discussed below in Section 3.5.2.a.



(a) Single Antenna. Large reflected signal received by antenna.



(b) Two Antennas. Only small portion of large reflected signal is incident on receiving antenna.



(c) Two Antennas. Only small reflected signal; very little of transmitted energy incident on object.

Figure 3.1.- Inherent advantage of bistatic system.

d. <u>Target Characteristics</u>. As for the microwave case, the the ratio of wavelength to target dimension is a crucial parameter. Acoustic wavelengths for a reasonable system would be in the range from 1.5 to 0.3 cm about one-half to one-tenth of those for a 10-GHz microwave system. Thus, a high degree of spatial resolution would be obtained. However, for a crash sensor it is not clear that a resolution of less than 5 to 10 cm is needed. Whether this aspect is of particular value depends on whether one can devise means to utilize the added information.

The important question here concerns the reflection coefficients of the various obstacles to which the system is likely to be exposed. For acoustic waves, this coefficient is a function of bulk modulus and density. Thus, it seems reasonable to anticipate a good correlation with mass (probably better than for microwaves), which is highly desirable. Absorption as in the case of fur on an animal or a hedge might well aid in reduction of false alarms. Indeed, these considerations are the basic reason for examination of ultrasonic systems. Experimental tests are necessary, of course, to confirm or refute these estimates. On the other hand, objects made of cardboard, wood, glass, etc., may also give rise to a large reflection, presenting a special false alarm problem.

e. <u>Receiving Transducer</u>. Regardless of the sensing method used - whether pulsed, coded, or cw - the bandwidth requirement will be at least that of a cw doppler system for equivalent information. Recall from part 3.4.3.a. that for the microwave system,

$$\frac{f_d}{f_o} = \frac{89.6}{c} \times v_{mph}.$$

For sound, c = 33,100 cm/sec.; therefore,

$$\frac{f_d}{f_o} = .0027\ v_{mph}.$$

So to provide for even a 125-mph closing rate, we must have

$$\frac{f_d}{f_o} = .35 = 35\%$$

In other words the receiving transducer and the entire receiving system must have a 35% bandwidth, with a center frequency between 20 and 100 KHz, and a relatively flat response in this range. While this can presumably be obtained, the cost remains to be determined. This question is still open. In addition, the problem of retaining such characteristics when the transducer is completely protected against weather extremes may be a very severe challenge, since resonant structures are generally part of any such shielding.

f. Receiver. Basic receiver circuitry should pose no major difficulty, although the greater the degree of sophistication in modulation, the greater the cost of demodulation circuitry and transmitter circuitry.

3.5.2 Environment

a. Variability of Propagation. This appears to be a major problem. As indicated above (3.5.1.c.), atmospheric attenuation at 100 KHz can vary from less than 1 dB/meter to approximately 10 dB/meter; for a 3 meter path, varying conditions can cause received signals from a given target to shift by 30 dB, a factor of 1000 in signal strength. If not compensated, this would completely rule out any use of amplitude measurements for triggering decisions. One solution would be to operate at much lower frequency, 30 to 50 KHz. However, this is likely to enhance noise problems (see part 3.5.2.c., following). It may still leave a 6-dB variability in return signal level and an associated problem in finding a transmitter level that guarantees triggering when needed in the worst case but does not allow false alarm in the case of low path attenuation.

b. Weather Protection. Protection of acoustic transducers against weather extremes presents clear difficulties. It is not difficult to obtain an hermetic seal, but typically this is accomplished by means of a resonant window which has a narrow bandwidth. Since high frequency operation inherently requires low mass of the moving parts, ice buildup on the front surface could completely destroy its transduction properties at the design frequency. In addition, this low mass is basically inconsistent with the structural strength required to survive sleet and hail, along with other objects such as sand, gravel, etc. As indicated previously, problems associated with the transducers are a significant part of the weakness of ultrasonic systems.

c. <u>Noise Level</u>. At present, this is an unknown quantity. Measurements of environmental noise are generally limited to the audible range, below 20 KHz. However, some informed speculation is reasonable. A commercially developed system for passive detection of automobiles operates at 40 KHz, where tire and other noise is apparently very high; motorcycles a hundred feet away have been found to produce a very high sound level at this frequency. As there is little likelihood that such noise is sharply peaked in frequency, it is reasonable to assume that the range between 20 and 100 KHz may be quite noisy. In addition to normal road noises, there are other common sources such as backfiring, explosions of any sort, thunder cracks, construction, manufacturing (generally close to highways, and almost certainly in the vicinity of parking lots) and the squeal of sudden brake applications in panic situations. It is extremely likely that the noise of a low-flying jet aircraft, particularly when taking off, contains very high intensity components over the entire range of interest.

A second possible noise source is air turbulence in the propagation path. In addition to normal wind flow and self-generated turbulence, air movements caused by nearby vehicles, such as large trucks in an adjacent lane, can severely affect an acoustic wave passing through that medium. The turbulence can have dimensions over which there is a pronounced change in velocity, direction, or density, either larger than, comparable to, or smaller than the acoustic wavelength in use. Therefore, a wide variety of effects can occur, including scattering, reflection, diffraction, and refraction. All of these will tend to add noise to the received signal and to introduce random variation into it. Indeed, this effect has been reported as experimentally observed at audio frequencies, and apparently increases as the square of the frequency. Thus, the effect of turbulence also seems to be a serious problem for acoustic systems.

A related noise source is rain or spray, where dimensions could conceivably be such as to approach signal wavelength; however, this factor should be considerably less important than turbulence. More serious is physical impact on the transducer by rain, sleet, sand, or pebbles. This will certainly introduce high-intensity noise components into the receiver; the resulting effect on system effectiveness remains to be evaluated, but is clearly an area requiring study.

In short, further investigation is required for a definitive answer on all of these questions. However, noise does appear to be a very real problem for any ultrasonic system to be used in an automotive environment. It may be insoluble within reasonable cost and other constraints.

d. Vandalism. For an acoustic system, there are two facets to this problem. Not only can objects be so placed or thrown as to cause undesired deployment; triggering can also be achieved from use of an appropriate signal source, such as an ultrasonic whistle (perhaps a "silent" dog whistle) or a small firecracker, likely to generate substantial ultrasonic components. "False alarm" targets might be successfully excluded through use of a sufficiently high triggering threshold, but the false signal source may be impossible to defend against without going to considerable costly sophistication in signal processing.

3.5.3 Overall System Aspects

a. Inter-vehicle Interference. As indicated previously, an acoustic crash sensor will require a very broad bandwidth -- at least 30%. Further, propagation characteristics and other factors limit choice of frequencies to a small range -- above 20 KHz and probably below 100 KHz. Hence there are far fewer independent channels than in the microwave case, and one must assume that essentially all units can interfere with one another. Although atmospheric attenuation can be very high, it can also be quite low, and can not give useful protection from nearby sonar-equipped cars. It appears that some sort of coding scheme will be necessary so that the receiver will respond only to signals that it has transmitted. This will add an unfortunate degree of complexity and cost to ultrasonic anticipatory systems if it can be accomplished at all; only a limited amount of coding is possible in the time intervals involved for the frequency range in question.

b. Radiation Hazards. For the acoustic power levels planned, no radiation hazard should exist. Only enough return signal is required, after traversing a very short path, to be above the ambient noise level. On the other hand, an attempt to eliminate "false alarms" associated with special noise sources (jet planes or thunder claps, for example) by setting a very high threshold might lead to use of such intense pulses that consideration would have to be given to this factor.

(It has not yet been determined whether permissible levels in the audible range are valid standards for ultrasonic energy. This information can possibly be obtained from the medical literature.)

c. Cost. A basic system need not be excessively expensive. But to overcome all the actual weaknesses and problems discussed here might be very expensive. The receiving transducer appears to be the most challenging component so far as expense is concerned, with the parallel requirements on bandwidth and environmental protection. The very sophisticated modulation and signal processing circuitry necessary to attempt to deal with some of the other weaknesses of an ultrasonic system could also prove very costly.

d. Effectiveness. A single, basic ultrasonic crash sensor, under given conditions, might well provide a good predictor of impending collisions, with acceptable reliability and high discrimination against false alarms. However, the probable susceptability to atmospheric variations, general environment, ambient noise, and acoustic false alarms -- due to sounds, not actual objects -- along with what is likely to be substantial cost, make this a relatively unpromising path to follow.

3.6 CONCLUSIONS

As indicated, the constraints and difficulties associated with mechanical anticipatory sensing make it inappropriate to continue the TSC investigation along these lines, particularly in view of the limited resources available.

While not without substantial problem areas, microwave sensing appears to hold the greatest promise for this difficult application. Since many of the uncertainities can be resolved only through the attempt to construct a working sensor, and by careful test and evaluation of such a system, this has been the course followed. The sensor actually developed is described in Section 4.

Although acoustic techniques are apparently somewhat less likely to lead to a viable crash sensor, the above comments concerning the value of fabrication and test of an actual unit are also valid for that approach. In addition, in the course of this program, the microwave radar system developed at TSC was seen to be based on a system concept for which completely analogous acoustic realization is possible. Indeed, the same

signal processing circuit can be used for both microwave and acoustic sensors with only very minor parameter changes. Thus, it has been seen as appropriate to devote a significant amount of effort to the sonar approach as well. This task is described in Section 5.

SECTION 4
THE MICROWAVE CRASH SENSOR

4.1 INTRODUCTION

As discussed in previous chapters, microwave radar appears to be one of the most promising methods for pre-sensing automobile crashes. We have designed and constructed a microwave crash sensing system which has been installed in a domestic subcompact auto. It is now being tested and evaluated under a wide variety of operating conditions.

4.2 THE SYSTEM

4.2.1 General Description

The sensor is a simple cw microwave doppler radar system that operates at a frequency of 10 GHz and a corresponding wavelength of 3 cm. A block diagram of the system is shown in Figure 4.1. Separate directional antennas are used for transmitting and receiving; this configuration is called a bistatic radar system. The antennas are mounted at either end of the automobile's grille and are aimed so that the centerlines of their patterns cross at a point 1 to 2 meters ahead of the grille. For a microwave signal to be received at the receiving antenna, a target object must be present in the region of space intersected by the fan-shaped pattern of each antenna, so that some of the transmitted microwave beam is reflected or scattered into the receiving antenna.

The microwave signal source used at present is a Gunn diode that produces a continuous 100-mW microwave signal. This diode operates from a 12-volt car battery and with a current of approximately 0.5 amps. It is held in a waveguide mount which is fastened to a short section of waveguide incorporating a signal-sampling probe. The waveguide section in turn is fastened to the transmitting antenna. Figures 4.2(a), (b) show the diode in its mount, and show the mount fastened to the sampling proble section and antenna.

Signals from the signal-sampling probe and the receiving antenna are added together and fed to a microwave detector diode. The detector output voltage depends upon whether the signal from the receiving antenna adds in-phase or out-of-phase to the sample of transmitted signal. As a reflecting target in front of the auto moves one half of a wavelength relative to the the auto, i.e., 1.5 cm, the detector output voltage goes through a maximum and a minimum. In terms of the relative velocity of target and auto, the frequency at which the detector output

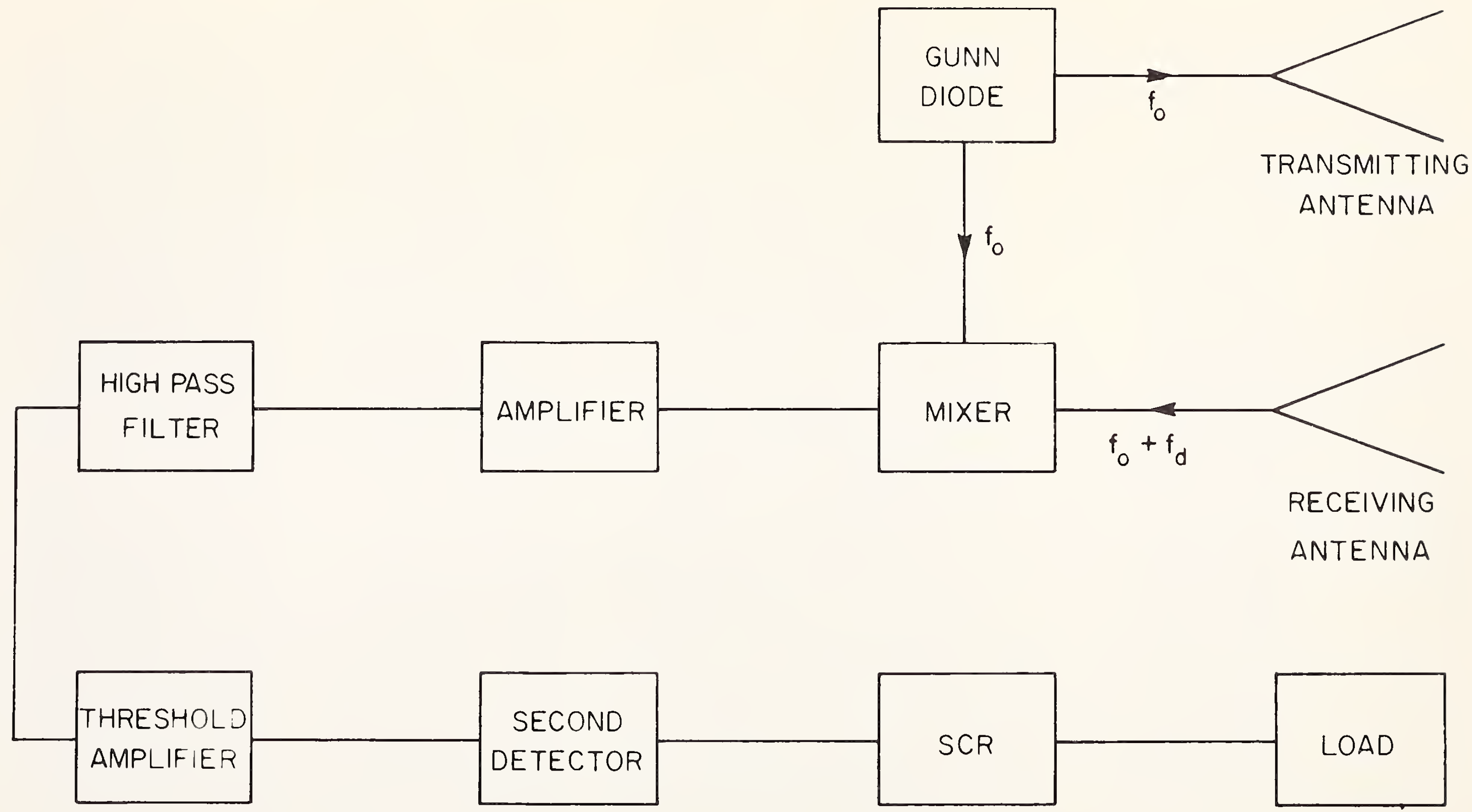


Figure 4.1.- Microwave system block diagram.

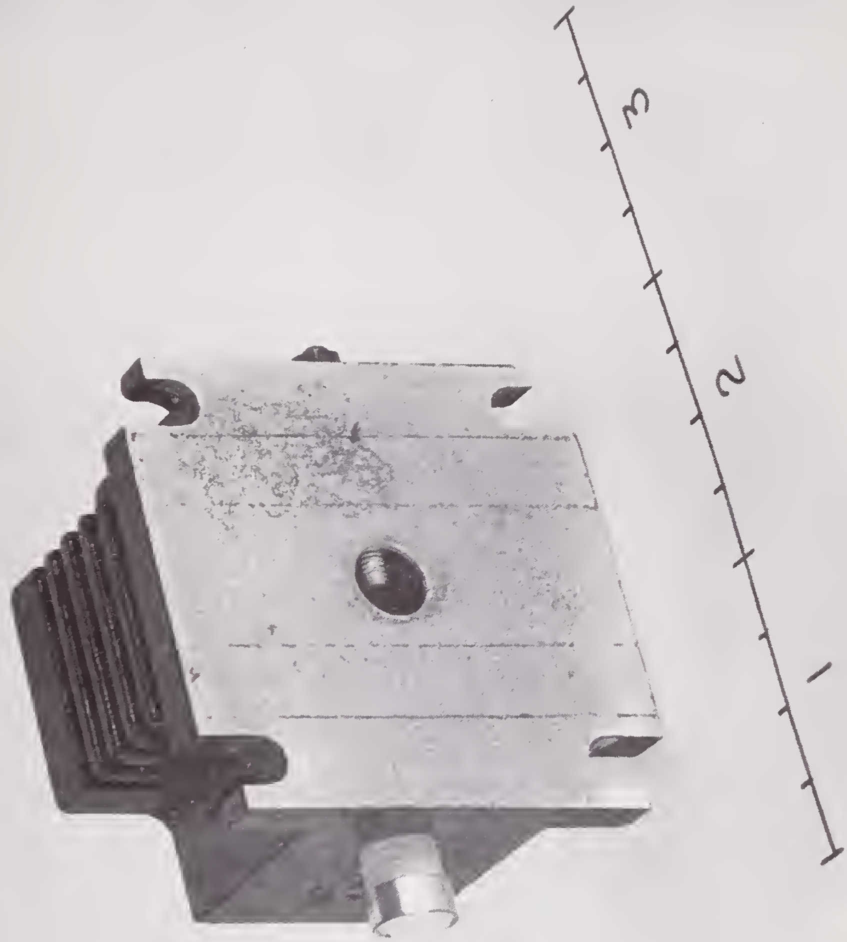


Figure 4.2(a.).- Gunn diode in mount.

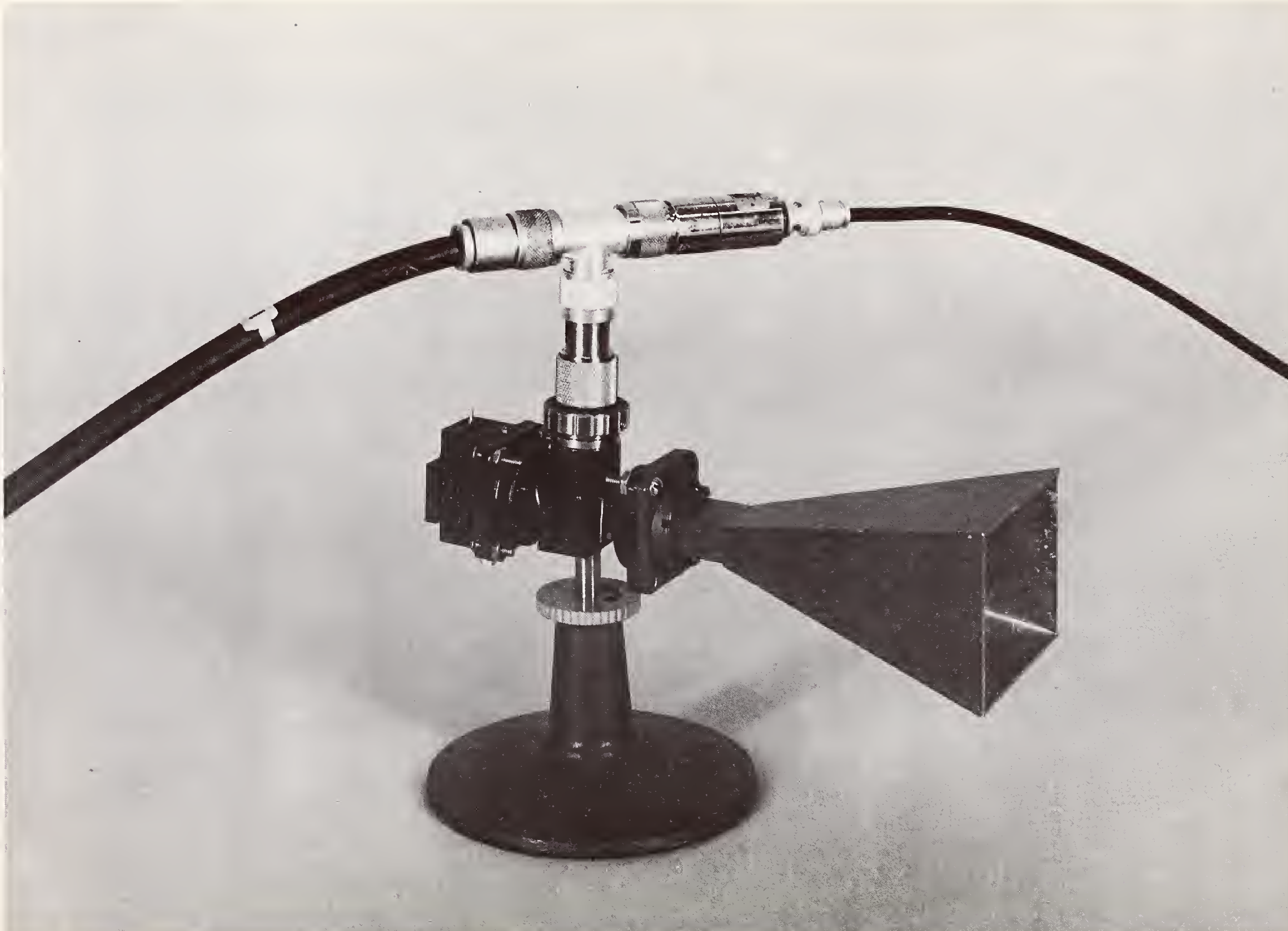


Figure 4.2(b.).- Gunn diode in mount attached to probe mount and antenna.

voltage varies, i.e., the doppler frequency f_d, is given approximately by the relation $f_d = 30\ v_{relative}$ Hz, where $v_{relative}$ is in mph. The detector output, i.e., the doppler signal, is seen to fall conveniently in the audio range, varying between 450 Hz at 15 mph to 6,000 Hz at 200 mph.

The doppler signal is amplified in a high-pass amplifier with a lower cutoff frequency of 450 Hz. This eliminates received signals due to targets that do not represent a great threat. The amplified doppler signal is then processed by a threshold amplifier for which the instantaneous output is +3 volts when the input is above an adjustable threshold value, and -0.5 volts for any smaller input. The purpose of this amplifier is to discriminate against targets so small that they would not be a threat in spite of high relative velocities.

The threshold amplifier output goes to a second detector stage consisting of a rectifier diode-resistor-capacitor combination which gives a staircase output ascending to some steady-state value in response to a square-wave input. When the staircase passes a selected value, it triggers the gate of an SCR, causing a light to flash on in our test system, indicating actuation.

The system design incorporates a number of built-in safeguards against "false alarms". The use of two antennas means that a small object cannot actuate the system by completely blocking one aperature. Several doppler cycles are needed for actuation, and this insures against actuation by transients generated in the automobile's electrical system. The system only "sees" the region where both antenna patterns converge immediately in front of the auto. This simple method of unambiguously determining target location helps minimize overall system complexity, also aiding reliability.

4.2.2 Antenna Considerations

The sensitivity of the microwave "front end" of the system is a function of target size, composition, and location. The variation of sensitivity as a function of target location depends upon antenna patterns, antenna positions on the auto, and directions of the main axis of the antenna patterns.

For a particular positioning and pointing of the antennas, and for a given target, the sensitivity S of the system varies approximately as

$$S \quad \frac{G_1(\theta_{1T}, \phi_{1T},)\ G_2\ (\theta_{2T}, \phi_{2T},)}{R_{1T}^{\ 2} R_{2T}^{\ 2}}$$

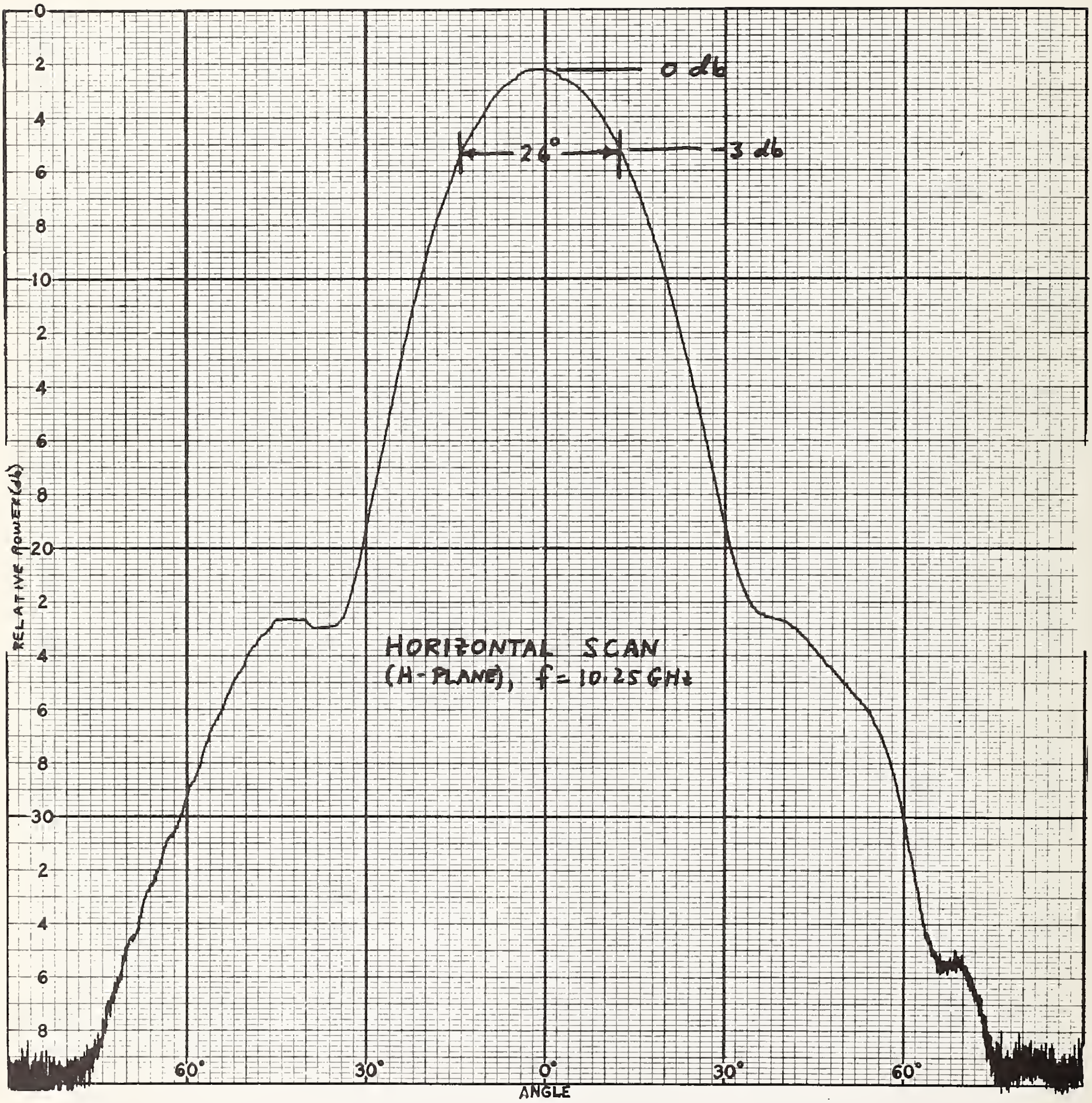


Figure 4.3(a.) - Variation of antenna gain in horizontal plane (H-plane).

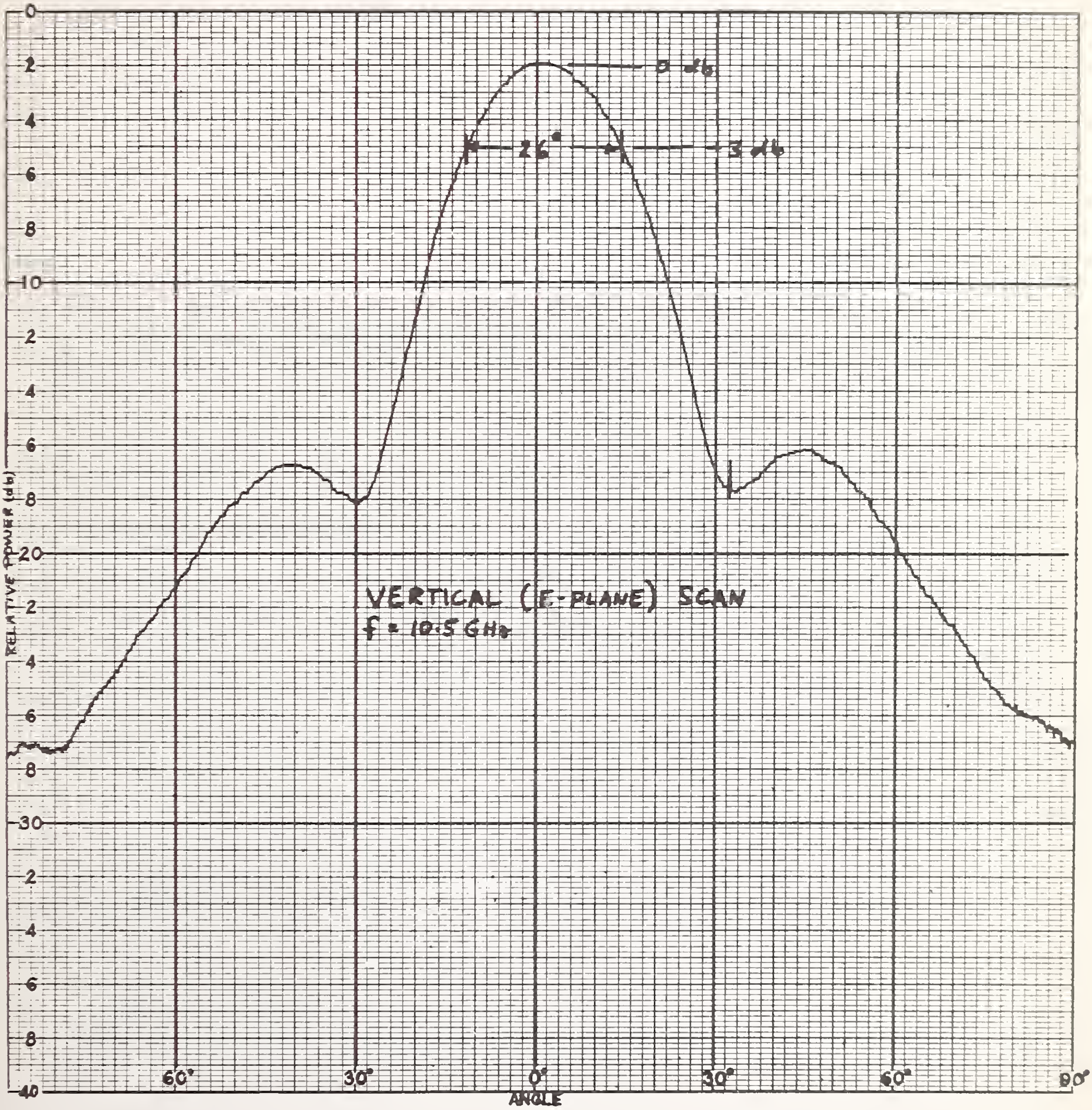


Figure 4.3(b.) - Variation of antenna gain in the vertical plane (E-plane).

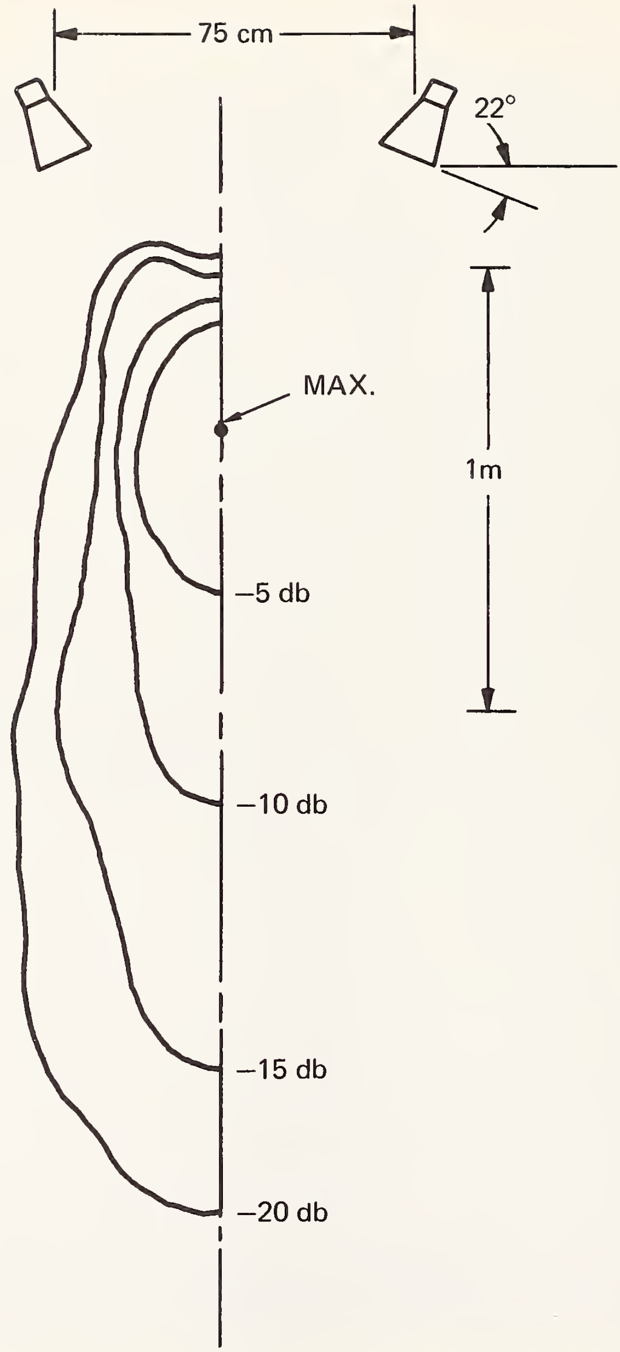


Figure 4.4.- Detection sensitivity pattern for Bistatic system.

where $G_{1,2}(\theta_{1,2T}, \phi_{1,2T})$ are the gains of the transmitting and receiving antennas respectively as a function of relative azimuth and elevation, and $R_{1,2T}$ are the distances from the target to transmitting and receiving antennas respectively.

The antennas currently being used are standard-gain horns with antenna patterns as shown in Figure 4.3. In tests to date, both antennas have been aimed inward at a 22° angle relative to the axis of the automobile. The resulting sensitivity pattern is shown in Figure 4.4. This pattern was measured by positioning a plane metal target of approximately 100 square inches crossection at various positions in front of the auto in the plane of the antenna pattern axis and measuring received signal strength with a calibrated receiver. The antennas, mounted on the test vehicle, are shown in Figure 4.5. Note that these antennas and antenna orientations are not to be regarded as optimum (the antennas should be as widely spaced as possible), but have proved to be useful in the early testing of this system concept.

The positioning of the antennas has a measurable effect upon the variation of doppler frequency as a function of target position, for constant relative target velocity. One doppler cycle is produced at the microwave detector output each time the total path length from transmitting antenna to target to receiving antenna changes by one microwave wavelength. There are ellipsoidal surfaces of constant relative phase, i.e., constant total path length, that have the antennas as foci; these are pictured in Figure 4.6(a.). A typical diagram of the resulting doppler frequency as a function of target position, for a target moving at constant velocity directly toward a point midway between the antennas is shown in Figure 4.6(b.).

Obviously this geometric effect causes an ambiguity in determining target velocity from doppler frequency. This factor must be taken into account in determining antenna characteristics and doppler thresholds. However, it should not prove to be a very difficult problem to surmount as far as overall system operation is concerned.

4.2.3 Signal Processing

Figure 4.7 shows the schematic diagram for the signal processing circuit, described in Section 4.2.1. The first-stage amplifier has a voltage gain of 800 and a lower cutoff frequency of 450 Hz. Filters at the input and output also have cutoff frequencies of 450 Hz. The characteristics of the two filters and the amplifier combined give a low-frequency roll-off of 30 dB per decade below 450 Hz. Figure 4.8 shows the gain of this amplifier-filter combination as a function of frequency.

Figure 4.5 - Antennas mounted on test vehicle. Microwave horns are just outside of parking lights.

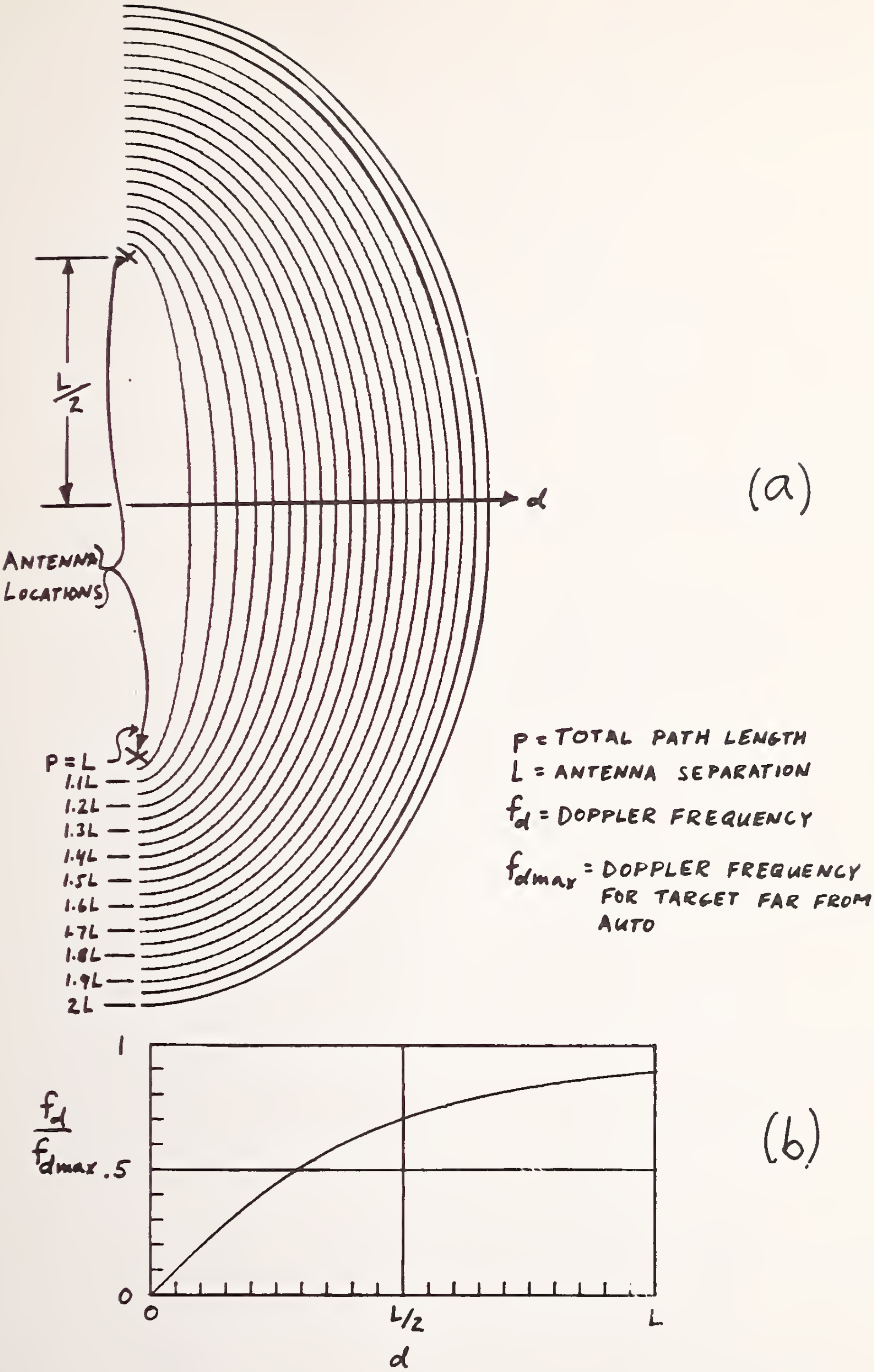


Figure 4.6(a. and b).- Ellipsoids of const nt relative phase

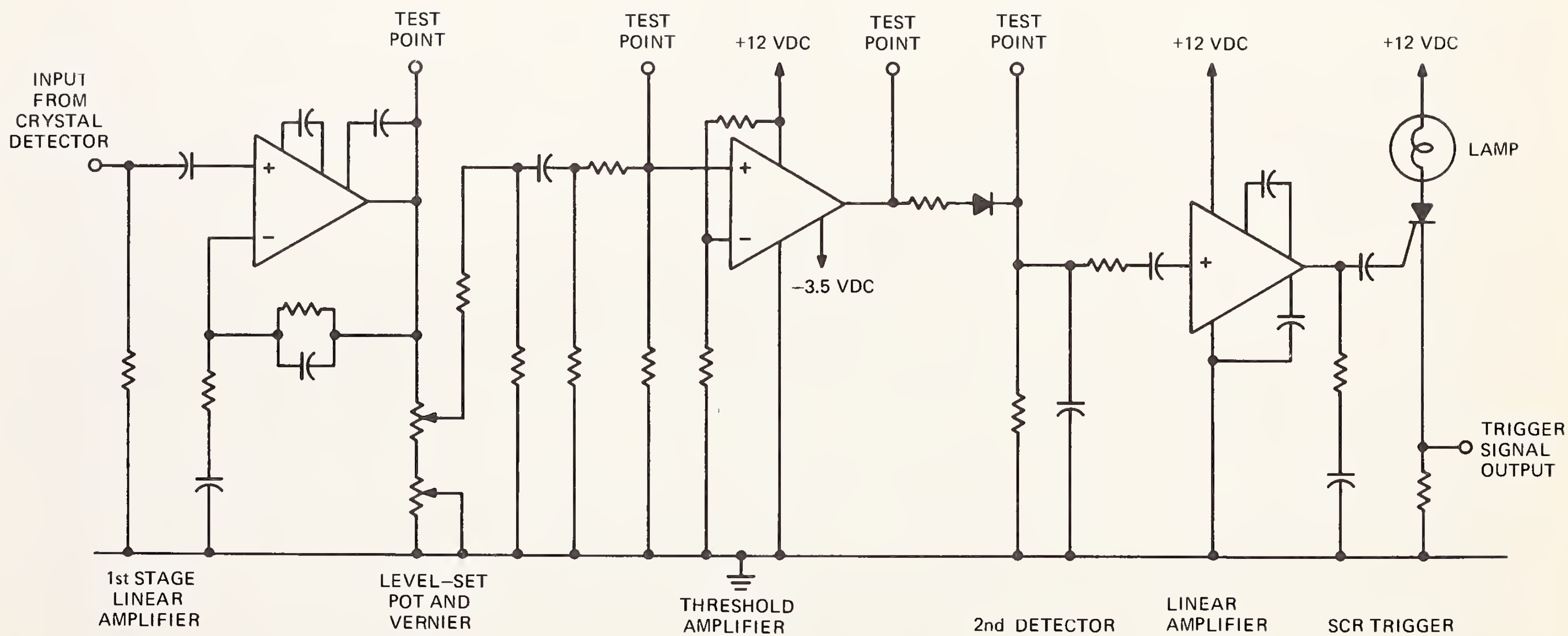


Figure 4.7.- Schematic diagram of signal processing circuit.

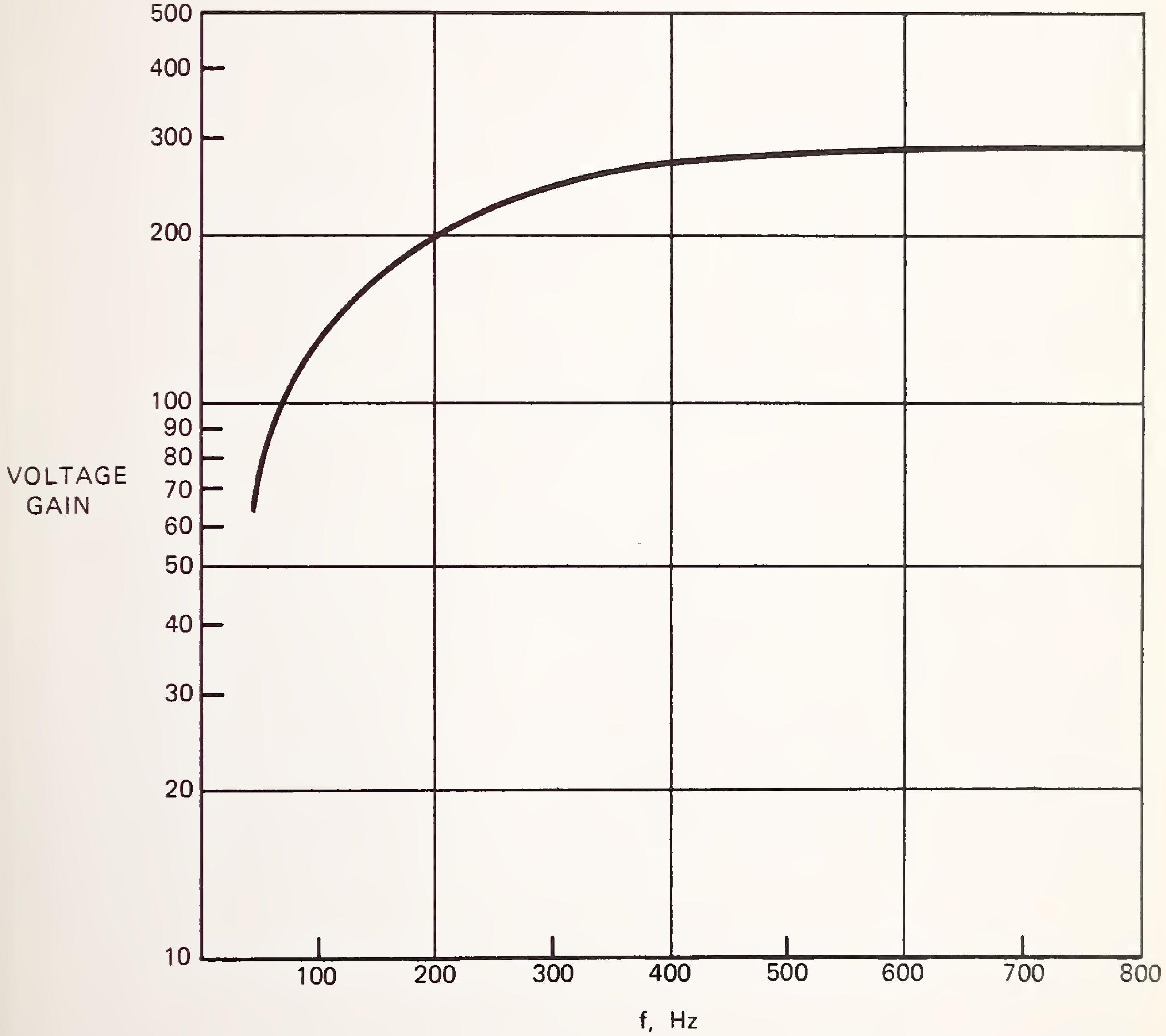


Figure 4.8.- Gain-frequency characteristics of amplifier/filter stage.

All of the signal processing circuitry following the detector diode is mounted on a printed-circuit board as shown in Figure 4.9. Figure 4.10 shows the "black box" that holds the PC board, switches, potentiometers, and test terminals for controlling and monitoring the system. This box is mounted under the auto's dash, as shown in Figure 4.11.

The potentiometers adjust the input level to the threshold amplifier to the desired sensitivity level for triggering. When signals appear at the threshold amplifier input with maxima greater than the threshold level, the threshold amplifier output is a square-wave signal of constant maximum amplitude. When the output reaches a certain level, the SCR is switched on, lighting an indicator light and actuating other indicating devices.

Figure 4.12 illustrates how the signal levels vary at various points in the circuit when a simulated doppler signal, produced by a tone-burst generator is applied at the input. By adjusting the parameters in the circuit it is possible to change the number of doppler cycles required for actuation.

4.3 RESPONSE TO VARIOUS TARGETS AND ENVIRONMENTS

4.3.1 Response to Test Targets

Our microwave crash sensor triggers when the automobile on which it is mounted encounters a simulated target of large size at velocities greater than 15-mph. This has been routinely shown by running into large cardboard boxes covered with aluminum foil. The sensitivity potentiometer can be adjusted to give various threshold target sizes. Adjustment can vary the minimum size for triggering of an aluminum foil patch from less than 10-square inches to more than 200-square inches. For a target of given size, triggering is also a function of sensitivity as a function of position. A large target always causes triggering slightly farther away from the auto than does a small target.

4.3.2 Response to Real and False-Alarm Targets

In order to measure the response of our system to various real and false-alarm targets, a series of field tests is being conducted. During these tests, an amplifier circuit with a lower cutoff frequency of approximately 10-Hz (.3 mph) is used in place of the high-pass circuit. The automobile is then rolled slowly up to various objects, and the linearly amplified doppler signal is recorded on a tape recorder. The tapes are played back in the lab, and the signals are observed and photographed using an oscilloscope. Stereo tape decks are used, with one channel for data and one for voice narrative.

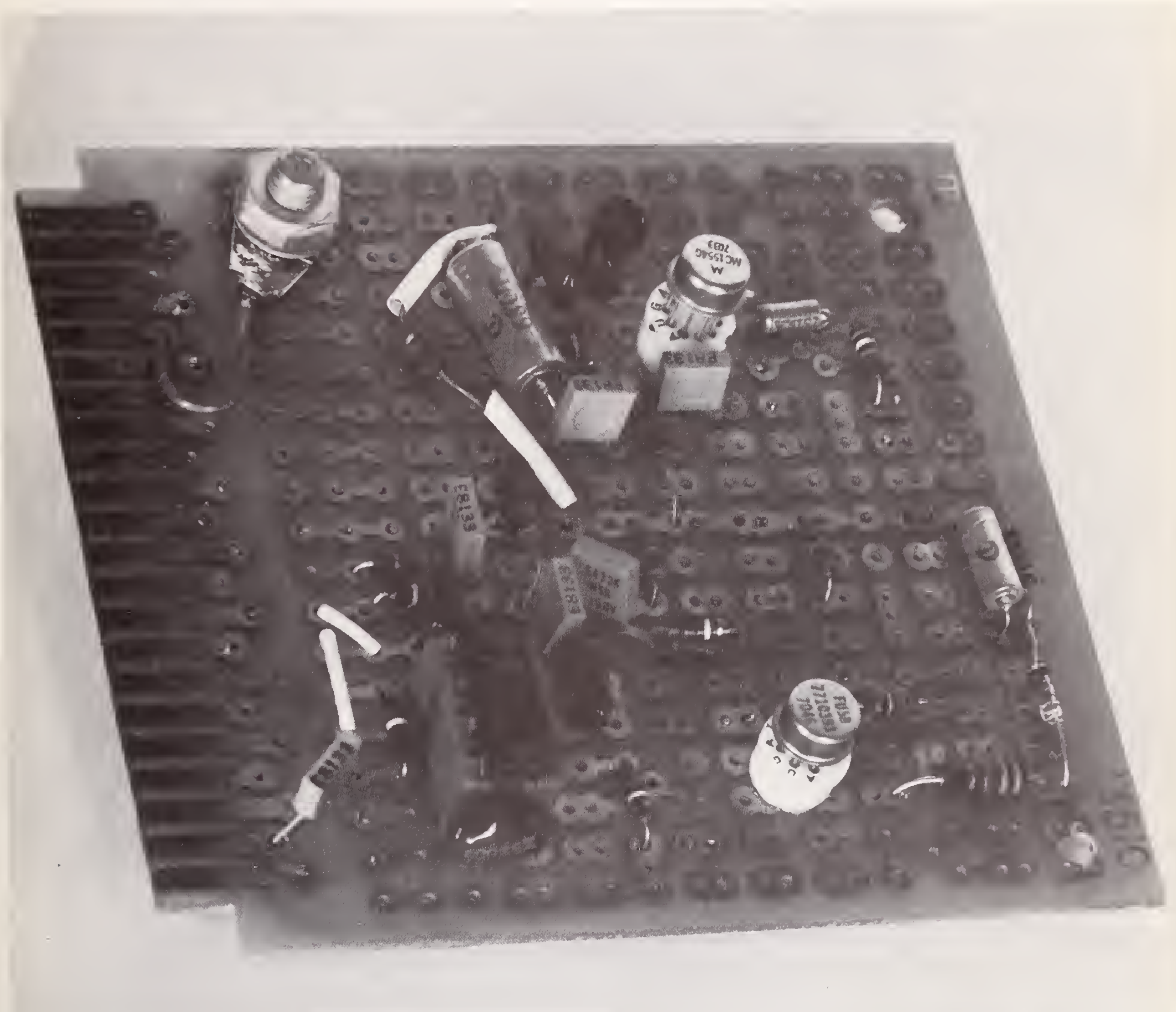


Figure 4.9.- Signal processing circuit.

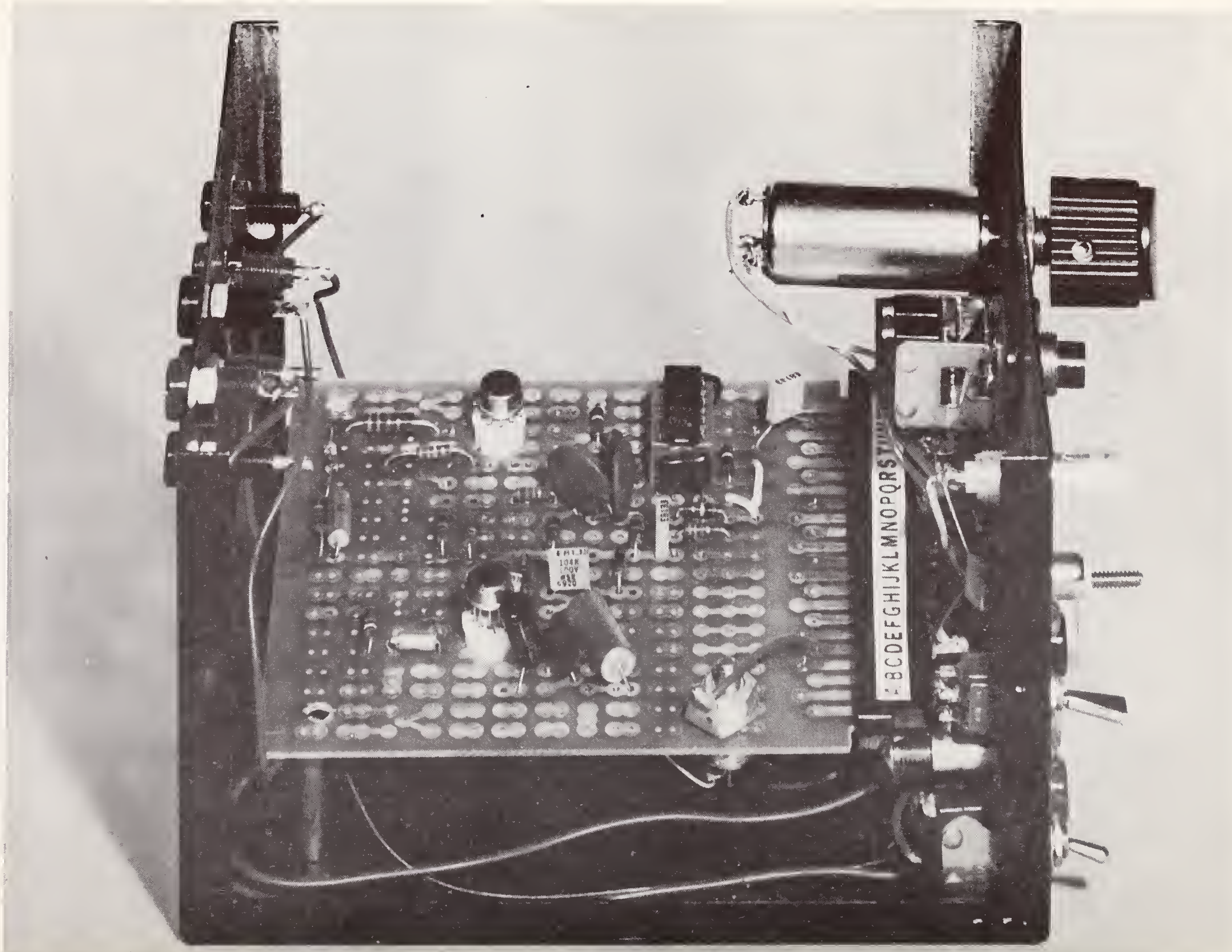


Figure 4.10.- Signal processing circuit, mounted in box.

Figure 4.11.- Signal processing circuit box, mounted in vehicle.

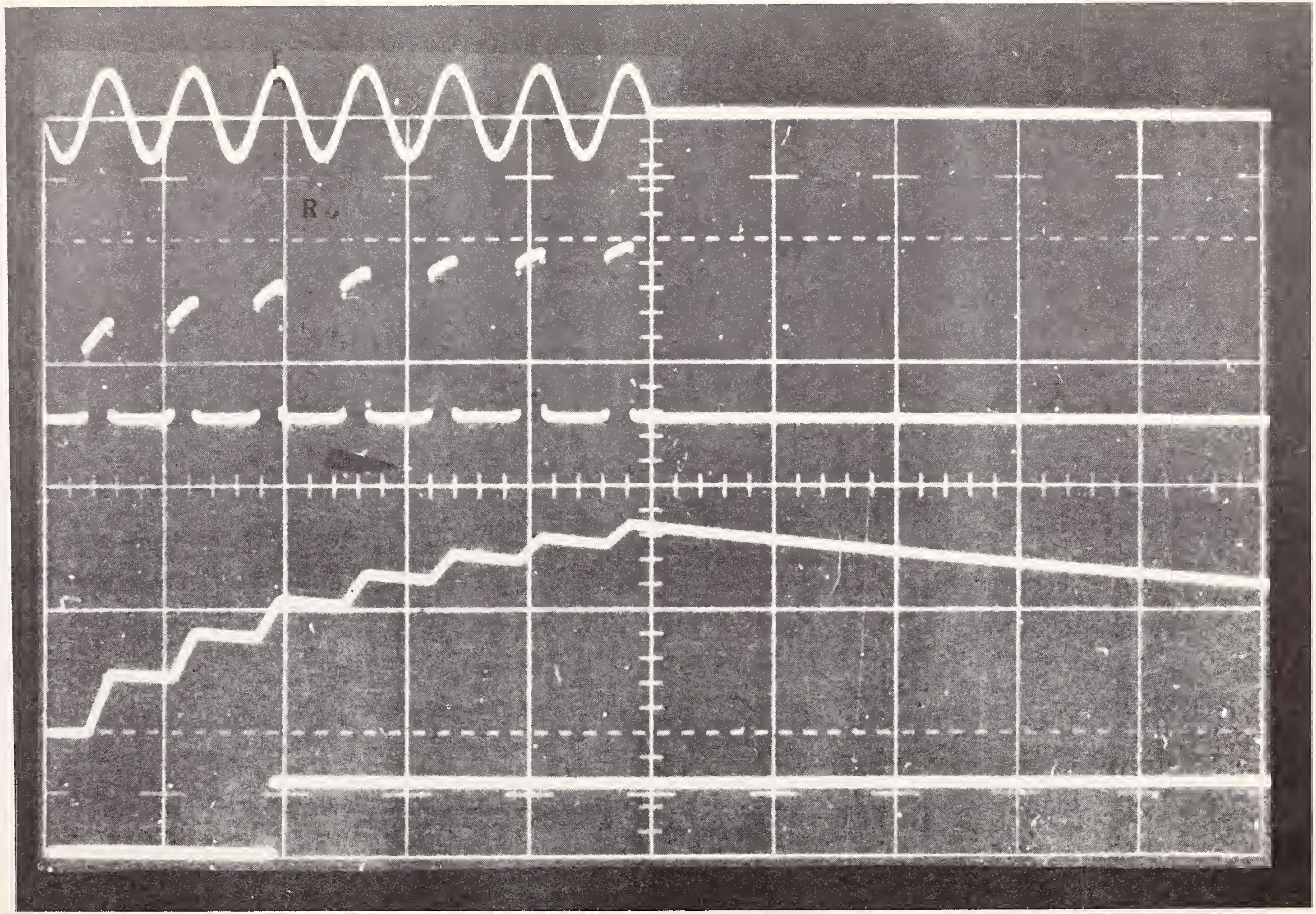


Figure 4.12 - Doppler signal at various points in circuit. A)First stage amplifier output. B)Threshold amplifier output. C)Second detector output. D)Trigger signal output.

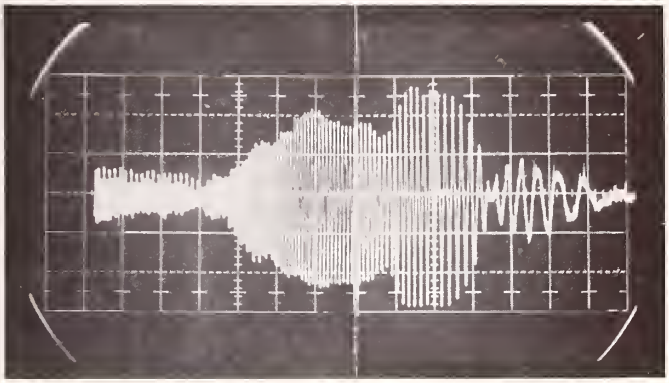


Figure 4.13(a.).- Doppler signature of a tree. 0.1 Sec/div. horizontal, 0.4 v/div/ vertical.

Figure 4.13(b.).- The tree.

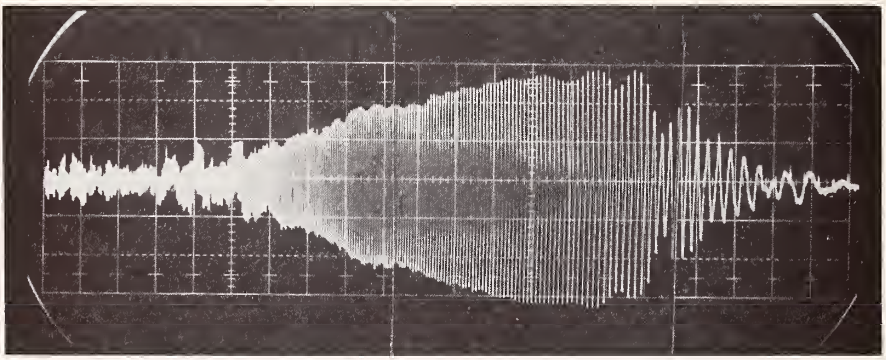


Figure 4.14(a.) - Doppler signature of a concrete post, 6" x 6"; 0.1 sec/div. horizontal, 0.4 v/div. vertical.

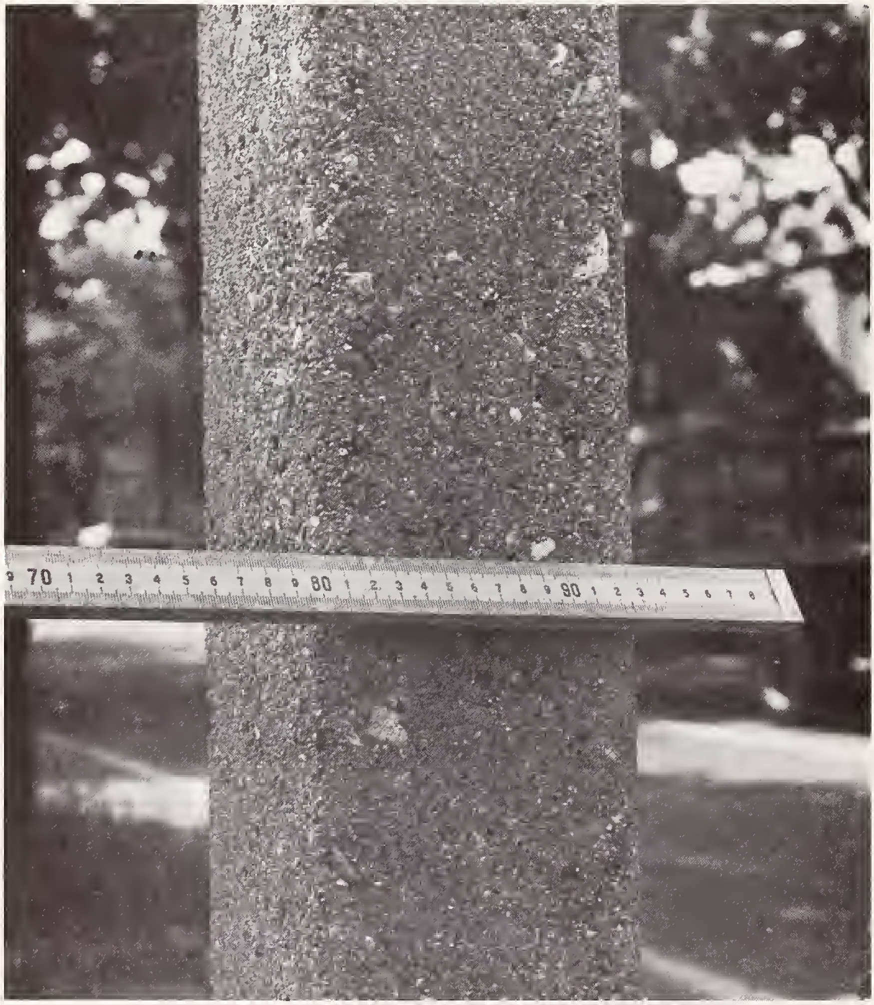


Figure 4.14(b.).- The post.

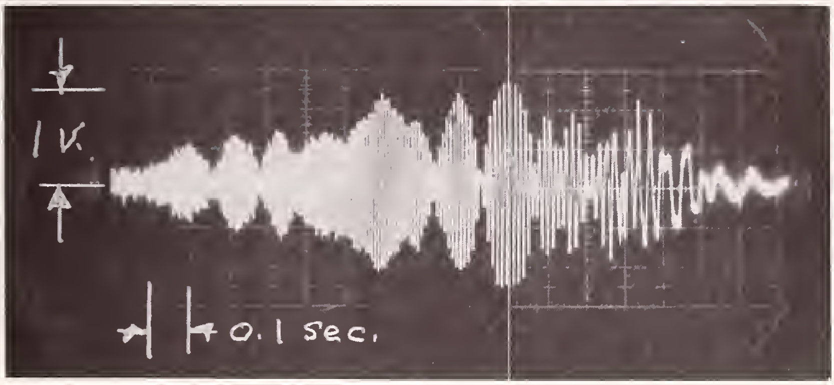


Figure 4.15(a.).- Doppler signature of a telephone pole.

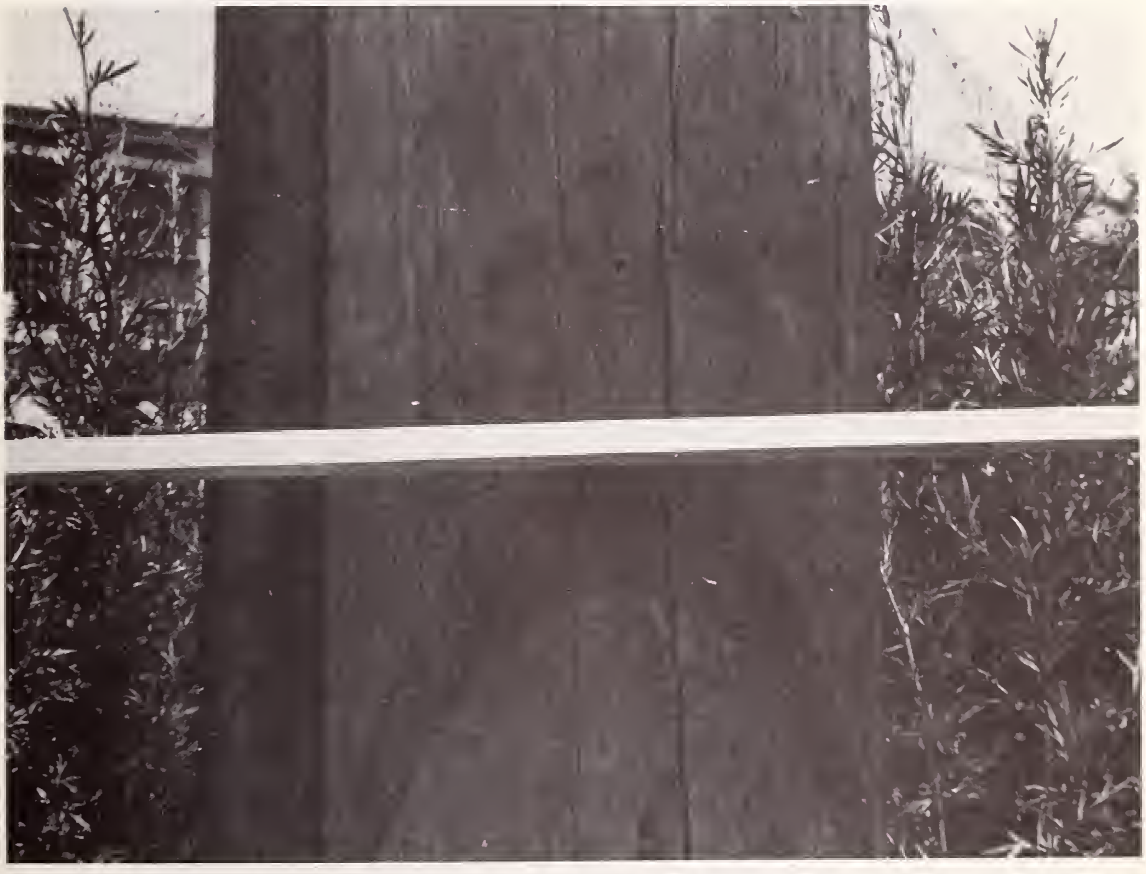


Figure 4.15(b.).- The pole.

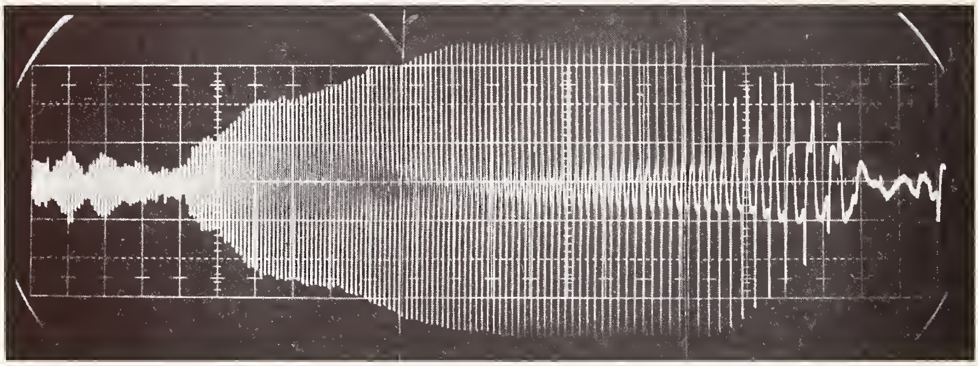


Figure 4.16.- Doppler signature of the rear of a domestic full-size sedan. 0.1 sec/div. horizontal, 0.4 v/div. vertical

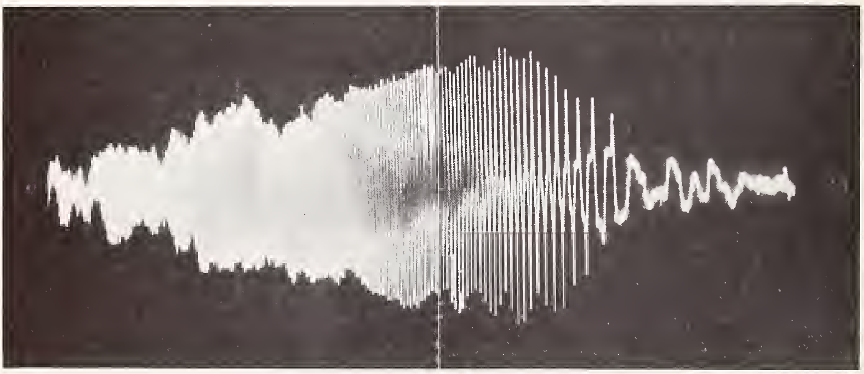


Figure 4.17.- Doppler signature of a concrete wall. 0.1 sec/div. horizontal, 0.4 v/div. vertical.

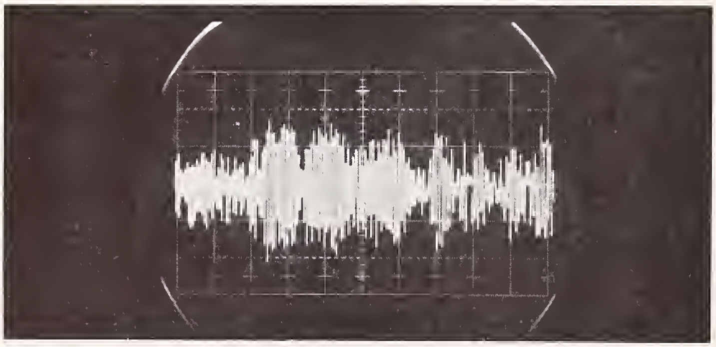


Figure 4.18 - Doppler signal obtained driving over corrugated metal roadway. 0.1 sec/div. horizontal, 0.4 v/div. vertical.

To date, doppler signatures of a sizeable number of objects have been obtained. Examples of some of these are shown in Figures 4.13 thru 4.18. In the pictures of the doppler bursts for every object except the corrugated bridge roadway, one first observes a low residual signal due to return from the road surface. As the target is approached, the signal amplitude increases. As the driver brakes to a halt a few inches from the target, the doppler frequency decreases, and the signal eventually falls to zero amplitude.

One sees that in the first five cases, the maximum signal amplitude is an order of magnitude larger than the normal road surface return for a large number of doppler cycles. However, driving across the corrugated steel roadway of the bridge produced a maximum amplitude fairly near that of some of the targets. More nearly optimum antenna patterns can reduce the road and bridge return substantially.

Much more data must be collected to determine what antenna patterns and circuit parameters give sufficient discrimination between real and false-alarm targets.

4.4 FUTURE WORK

Field testing as described in the previous section is continuing. The data now being obtained is being used in specifying parameters for different parts of later systems based on our current one. Extensive attention is being given to use of two or more parallel microwave front ends with spatial regions of high sensitivity oriented to give optimum spatial coverage. Advanced concepts for individual components are being investigated also. Characteristics of the antenna patterns in the vertical and horizontal directions are being studied to determine what patterns are optimum in light of environments encountered. Recent advances in antenna technology have led to X-band antennas with directional properties equal to horns that can be inexpensively fabricated in strip-line form. These antennas are small and rugged as well.

It appears that all of the electronics on the PC board could be fabricated in one 14-pin flat-pack, should the market warrant. A number of microwave manufacturers now have in development integrated microwave front ends for systems such as ours. These contain the microwave diode source, power sampler, antenna terminals, and detector diode all in one small rugged package.

One further area of current investigation is the use of a microwave crash sensor in series or parallel with other crash sensing systems to provide an overall system with characteristics superior to any single system. In such combined use, it is felt that the compromises necessary in simultaneously determining acceptable miss and false-alarm probabilities would be far less severe.

These topics will be covered more fully in later reports.

SECTION 5
THE ULTRASONIC SENSOR

5.1 INTRODUCTION

The ultrasonic acoustic (sonar) crash sensor developed at TSC is based on exactly the same principles of operation as the microwave sensor: it is a bistatic cw doppler system, with range determined entirely by the transducer patterns. Specific considerations relevant to each component were indicated in Section 3.5. Since both operating frequency and propagation velocity are reduced by approximately a factor of 10^6 from the microwave case, the carrier wavelengths and hence frequencies observed are quite similar: at 40 kHz the shift is 100 Hz/mph. The signal processing is identical to that described in Section 4.2.1, with the single change that the high pass filter must have a cutoff frequency of approximately 1600 Hz for a 15-mph threshold velocity. (Indeed, the same circuit has been used in testing.)

5.2 THE SYSTEM

The signal source which has been used is merely a simple transistor oscillator operated from 12 Vdc. The receiver consists of an amplifier and mixer diode, followed by a low-pass filter to eliminate the 40 kHz carrier . Figures 5.1 thru 5.3 show, respectively, a block diagram of the acoustic portion of the system, circuit schematics of the oscillator and receiver, and a photograph of the actual circuits. The transducers used experimentally are hermetically sealed, although not inherently suited to external mounting without further weatherproofing. Unlike the microwave case, where basically suitable antennas, with appropriate all-weather "windows", are readily obtained, there are few commercial applications, and thus a very limited availability of transducers with appropriate characteristics. There is not a great problem with the transmitting unit, which can be narrow-band, but - as indicated in Section 3.5.1 - obtaining the required bandwidth in a sensitive, low-cost receiving transducer is a more difficult task. (The major present market for such components is intruder alarm systems, where motions of .1 to 10 mph (10 to 1000 Hz) are of special interest.) However, the low available bandwidths are adequate for the most important class of tests, in which the vehicle is rolled slowly up to various obstacles (with no high-pass filtering for velocity discrimination) for measurements of acoustic reflectivity. It is by this means that various potential targets may be characterized and system effectiveness estimated. Also, a narrow band is sufficient for measurement of environmental noise in the vicinity of 40 kHz.

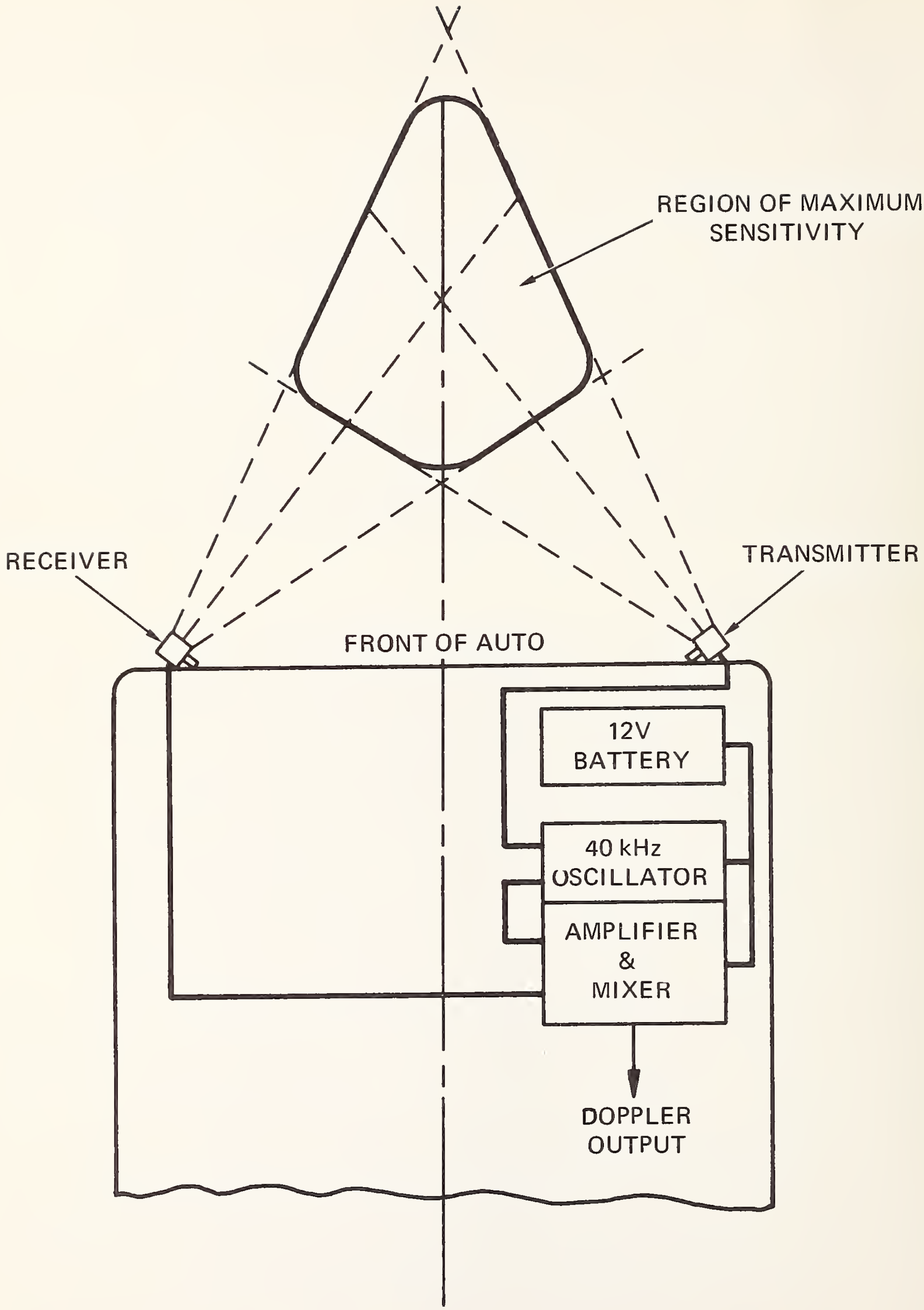
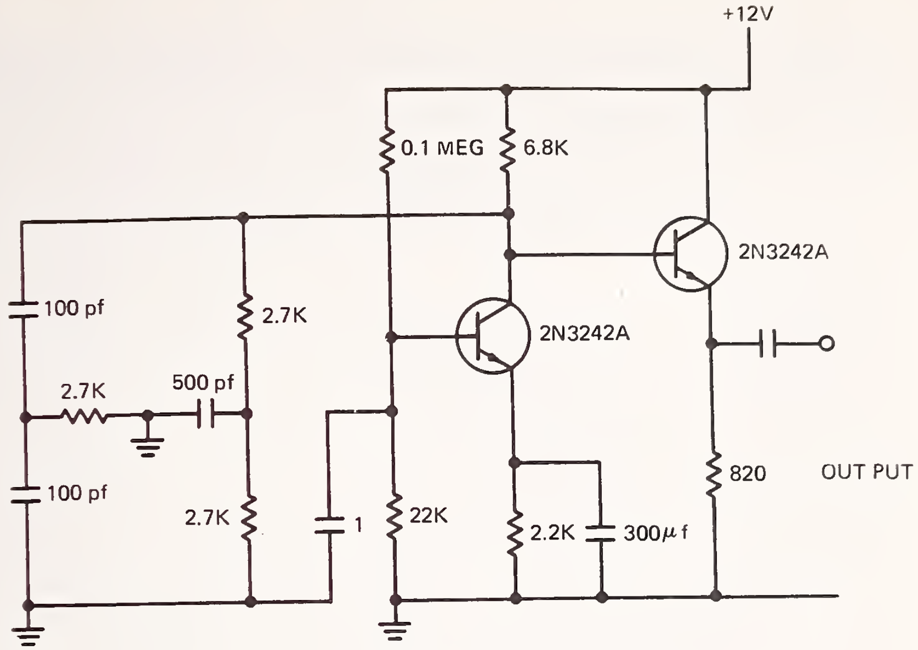


Figure 5.1.- Acoustic system block diagram.



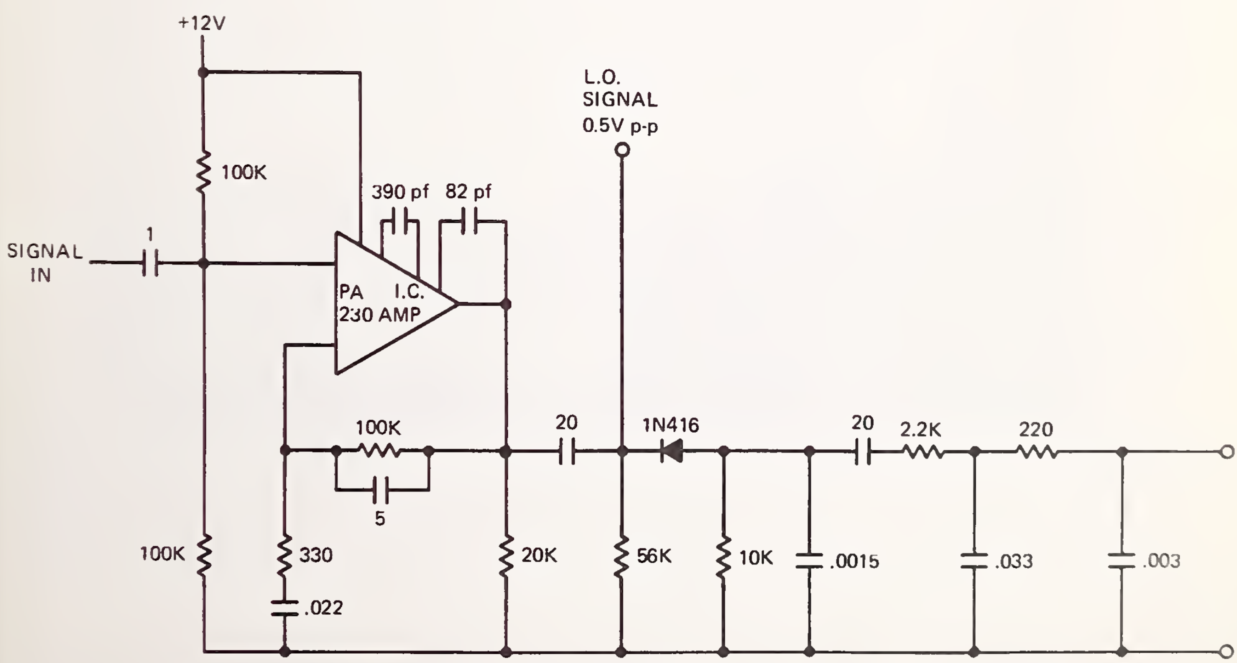


Figure 5.2.- Oscillator and receiver schematic diagram.

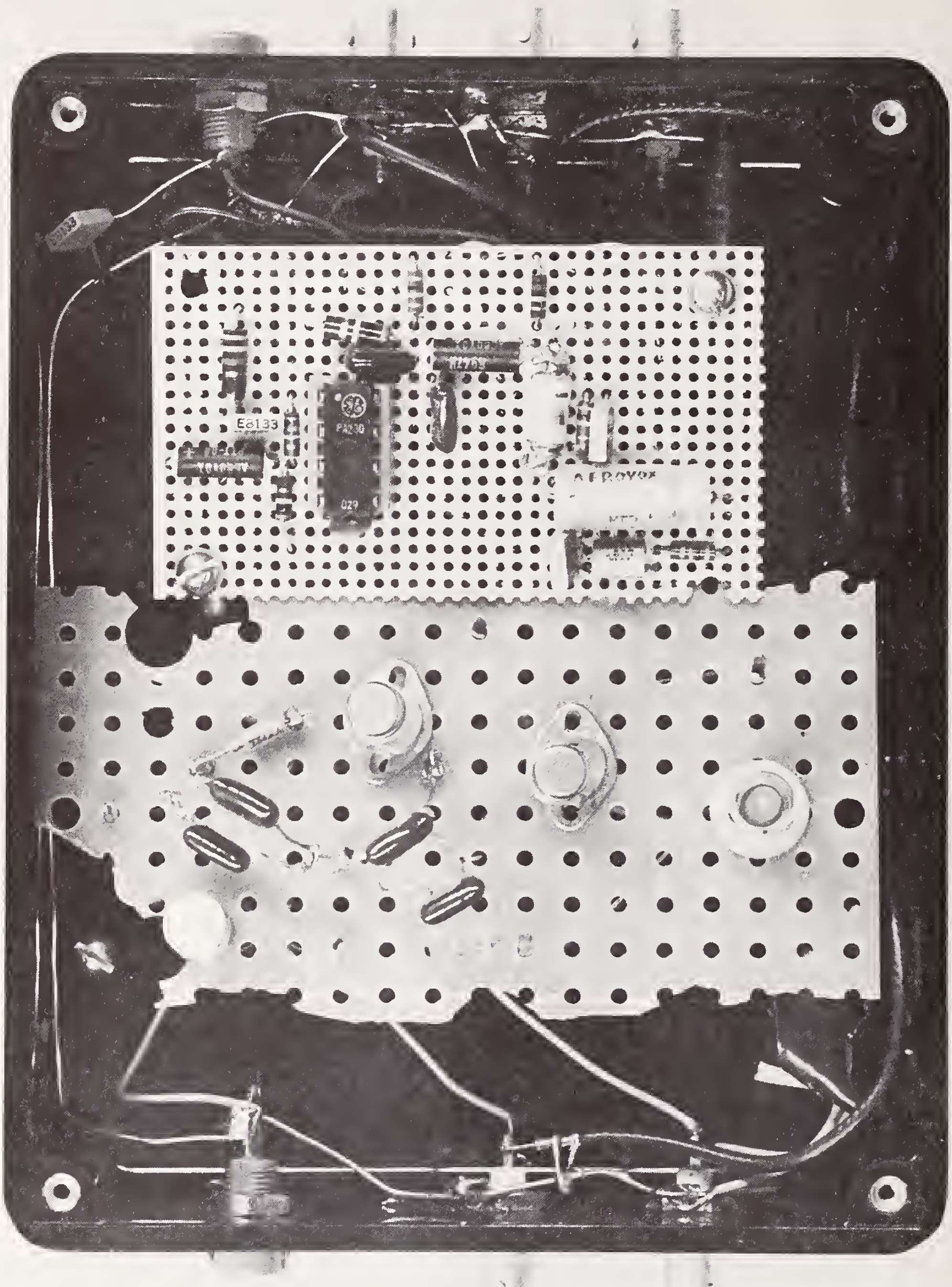


Figure 5.3.- Actual circuit.

Due to the less broadly developed nature of ultrasonic technology in the frequency range of interest, this portion of the TSC program has required more emphasis on characterization and improvement of components, particularly transducers. Several types of crystal transducers have been tested. They are small, rugged, and relatively inexpensive, two resonating near 40 KHz (one with a mesh-covered aperture, the other hermetically sealed), and one tuned to 22.5 KHz (hermetically sealed by an aluminum diaphragm). Measurements have been made using identical transducers as transmitter and receiver, mapping the directional propagation characteristics and observing reflections off several different types of surfaces. Attempts have been made to focus the beam with a simple cylindrical horn. Comparison of data taken with and without such a horn showed improvement in this respect. The higher-frequency unit permitted better focusing than the other, as expected. Reflected signals and phase shift (or doppler effect) with motion were studied with smooth surfaces of metal, wood, glass and cardboard. All gave pronounced reflections at several feet at the specular angle, although quantitative reflection coefficients have not been determined.

A prototype system was set up with a transmitter at the center, flanked by two receiving tranducers 24-inches on each side tilted inward at an angle 20^{o} off axis. The purpose of this geometry was to create an extended zone of about 40 inches wide, 30 inches in front of the array. However, significant sensitivity was still observed as close as one foot and as far out as six feet. Quantitative polar-coordinate plots have been made of several units using a smooth cylindrical horn, as well as one lined with a sound absorbing material. The latter showed an improvement in resolution by reducing the angular width at 1/2 maximum intensity by approximately a factor of two. In addition, a number of baffle structures have been designed to minimize impact of miscellaneous road debris--pebbles, ice, insects, etc.,--while not interfering with the acoustic behavior. Baffles have been built which show no loss of signal strength and will eliminate direct impacts, although bandwidth has not been measured (being limited by the transducers in use) and the actual road effectiveness remains to be determined. Figures 5.4 thru 5.7 show, respectively, a 40-kHz transducer, the baffle design, a completed unit, and graphs of the transducer pattern with and without baffle.

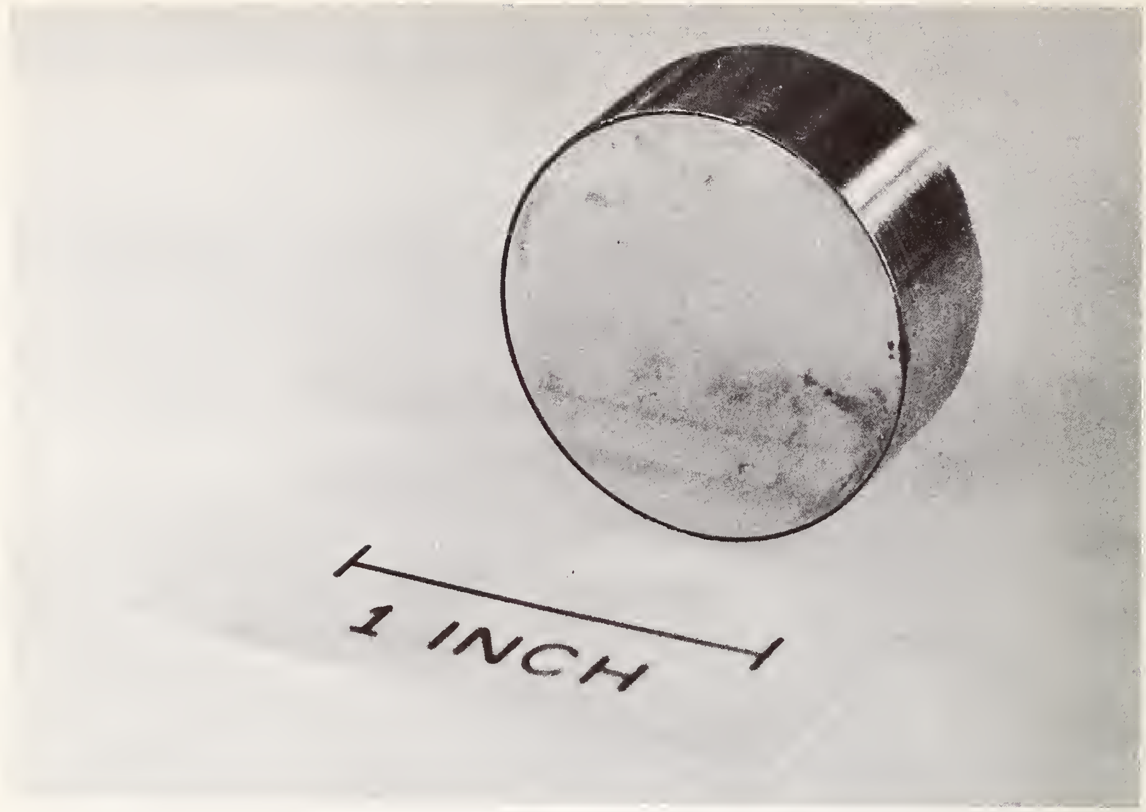


Figure 5.4.- Transducer.

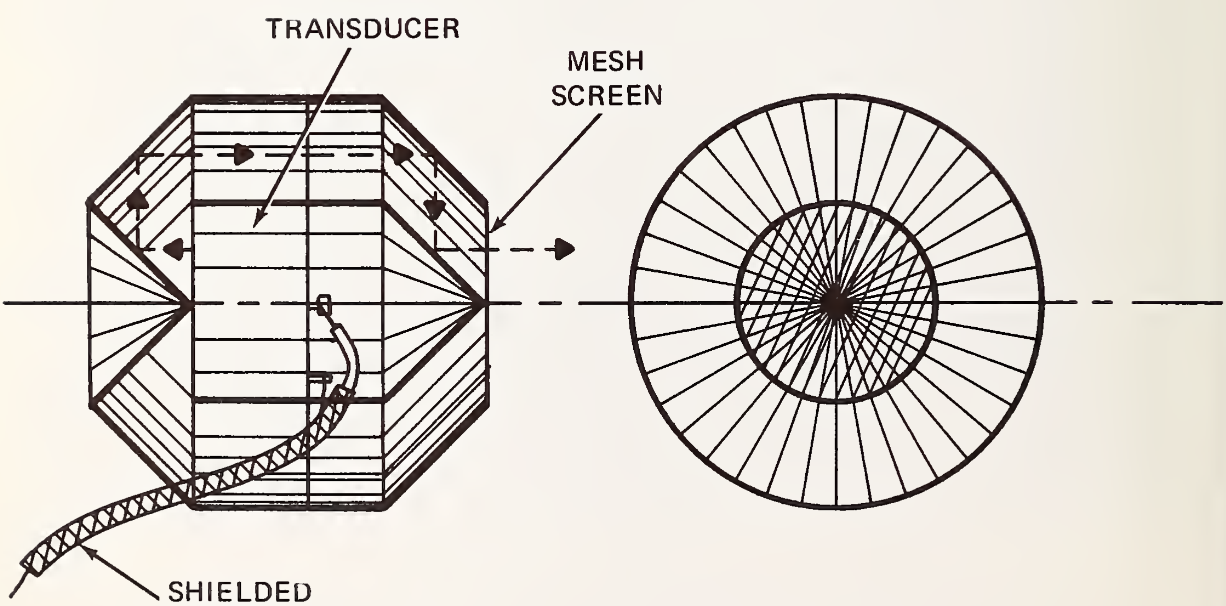


Figure 5.5.- Baffle design.

Figure 5.6.- Completed baffle.

The most recently obtained 40 kHz transducers, hermetically sealed, can achieve substantial bandwidth by means of electrical matching circuits, as is generally the case for resonant devices. A useful technique for further study will be selection (if possible) for use as the transmitting transducer a unit with a resonance frequency approximately 1500 Hz below the low frequency cutoff of a broad-banded receiving transducer. This would provide the required low velocity threshold directly.

5.3 SYSTEM TESTS

Laboratory tests of this system have been carried out for both component characterization and preliminary sensor evaluation. These provide some insight into sensitivity and target discrimination. For fixed transmitted signal and geometry, at 40 kHz, with a total path length of approximately five feet, typical received signals were: metal, 30 mV; plywood, 2.5 mV; plexiglass, 2.0 mV; cardboard, 2.0 mV; and ceramic, 3.5 mV. These figures show that ultrasonic waves are relatively insensitive to the composition of several common materials. Substantial return has been observed for the human body moving toward the system, suggesting that a similar response would be found for large (or even medium sized) animals, as well as pedestrians.

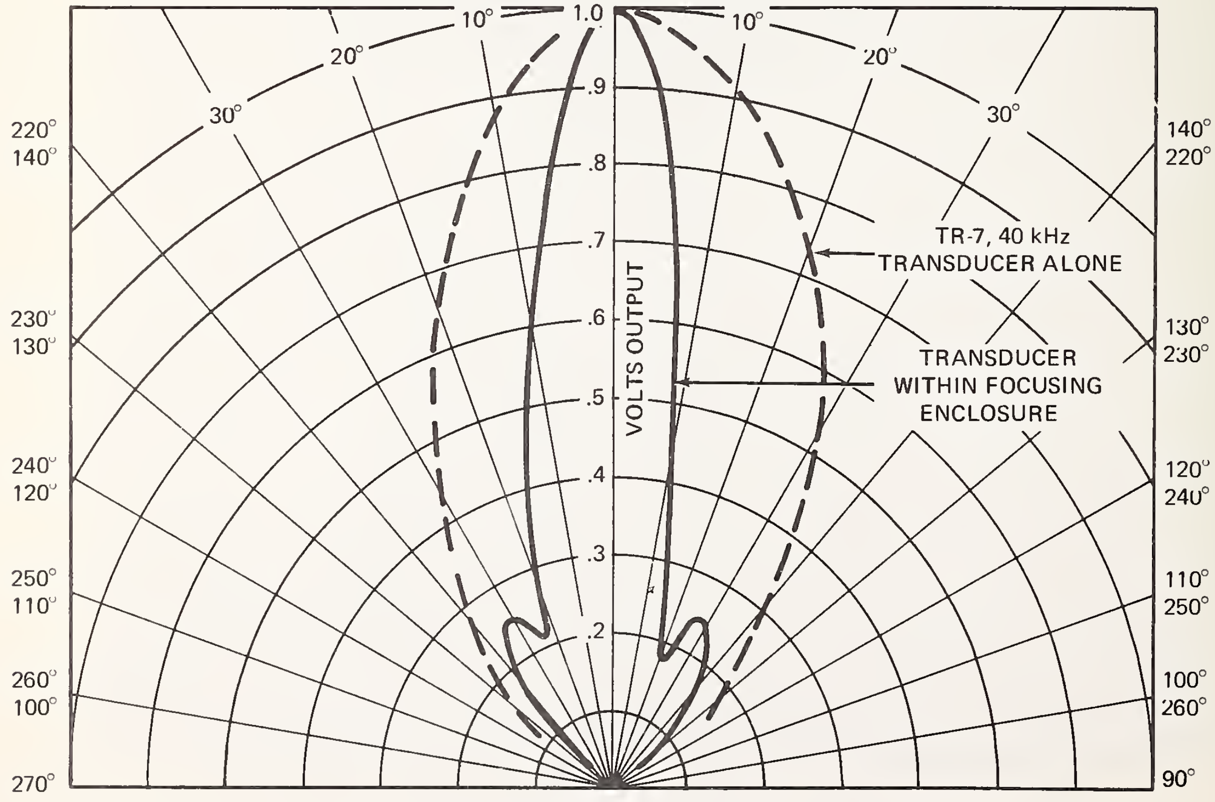


Figure 5.7.- Transducer patterns with and without baffle.

The system described above has also been mounted on the test vehicle on several occasions; transducer location is seen in Figure 5.8. (In any functional system, they would be mounted flush with the front of the automobile.) Signal processing is as for the microwave system (Section 4.2.3), used in the "all pass" (10-Hz lower cutoff frequency) mode. The bandwidth of the transducers used to date is only several hundred Hz, so only roll-up tests have been possible. Various difficulties with the electronic circuitry - common in experimental systems - have delayed acquisition of quantitative data. Measurement of acoustic reflectivity (at 40 kHz) of various targets should begin in the very near future. Qualitative observations indicate substantial return from a number of representative targets (vehicles, concrete walls, trees, telephone poles, fences, etc.), but it is not yet clear whether acceptable target discrimination will be possible. No large "false alarm" signals were seen when driving in traffic. Preliminary indications also suggest the possibility of significant susceptibility to noise, but substantial further testing will be necessary to determine the degree to which either circuit saturation or false signal indications will be a problem. Fugure testing will make use of a broadband microphone as a receiver, permitting more realistic operation and evaluation of the system.

Figure 5.8 - Acoustic transducers mounted on automobile. They are shown mounted on upright posts.

SECTION 6
PRELIMINARY CONCLUSIONS

6.1 ESTIMATION OF EFFECTIVENESS OF ANTICIPATORY SENSORS

Overall effectiveness of anticipatory sensors, both in general and for specific realizations, can only be estimated. It is necessary to obtain a considerable mass of accident data which - in some cases - is not the information normally recorded. Although the many variables involved make convenient a quasi-mathermatical formulation, which is described in Appendix II, it is by no means intended that this imply the potential for accurate prediction. However, for the limited purposes of this discussion, it is sufficient to note that one must relate the sensor and restraint characteristics to the total population of accidents to determine the percentage of cases for which a given dynamic restraint system will be of benefit, as well as the degree of improvement attainable. For example, current dynamic systems offer no benefits in rear, side, or rollover accidents, regardless of sensor. The microwave sensor may prove ineffective against a variety of targets, such as telephone poles and small trees, and may further limit the impact angle for which triggering is obtained. Thus, by such reasoning, one can immediately define a large class of accidents (and a very substantial number of deaths) which will not be affected by a microwave sensor/inflatable restraint protective system. On the other hand, the toll in death and injury resulting from frontal collisions with impact speeds of 30 to 60 mph may be very significantly decreased by means of anticipatory sensing. (Recall the effectiveness of prior activation as indicated in Section 1.2.1 and Appendix I.) Indeed, the severity and frequency of frontal collisions at higher speeds (above 30 mph), and the basic high-G deceleration capability of existing inflatable restraints suggest that the importance and potential value of predictive sensing may be very substantial. Accurate estimation of the possibilities requires information as to three aspects: (1) system operation (response to true and minor targets), (2) system reliability (Section 6.2) and accident data. In the last category much information exists and is constantly being augmented; in coming months it will be used in this program to permit meaningful evaluation.

6.2 RELIABILITY

6.2.1 Introduction

The ultimate success or failure of a dynamic passive restraint system, particularly when anticipatory sensing is utilized, will probably be determined by considerations relating to reliability. This term has been used earlier in a rather

restrictive sense, but is here intended to have quite general meaning. While this brief discussion will, to some degree, repeat the criteria of Section 1.3, and parts of 3.4 and 3.5, it is included to summarize those factors which can directly produce or inhibit triggering.

6.2.2 Inadvertent Actuation

The basic sources of inadvertent actuations have already been discussed. The problem of "false" targets - obstacles which induce deployment when not needed - is typically the first to come to mind, but is not necessarily the most important. In truth, it is quite rare for vehicles to strike objects sufficient to trigger microwave radar sensors (for example). While animals can have relatively high radar reflectivity, they are generally sufficiently low (cats, dogs) or small (birds) that the threshold for actuation will very seldom be exceeded. An informal survey suggest that most drivers can recall no such experiences, assuming that birds can be eliminated. The most threatening false target (in terms of frequency of exposure) is a heavy spray or sheet of water. (This sensor response will be examined in the near future.)

There is little to be added here on inter-vehicle interference, vandalism, and environmental noise, save to comment that all appear to be controllable, at least for microwave systems, to an adequate degree. (Such control may, however, add significantly to system cost and complexity.)

It appears that by far the more challenging aspect of reliability is the electronic circuitry itself. Virtually any sensor can be considered ultimately as a threshold device - if some voltage, current, charge, or magnetic field exceeds a set value, actuation occurs. The situation is illustrated in Figure 6.1. There will be an optimum value for the threshold, and presumably some allowable range of variation. But if the threshold should for any reason drift too far down, susceptability to false alarms can increase dramatically.
When this circuit stability requirement is viewed in the context of the automobile environment, with the additional consideration that a truly viable system could ultimately be installed in 100,000,000 vehicles, the required mean time before failure becomes very long indeed for public acceptability.
It remains to be seen whether even the wonders of solid state electronics will permit performance on that scale at an acceptable cost.

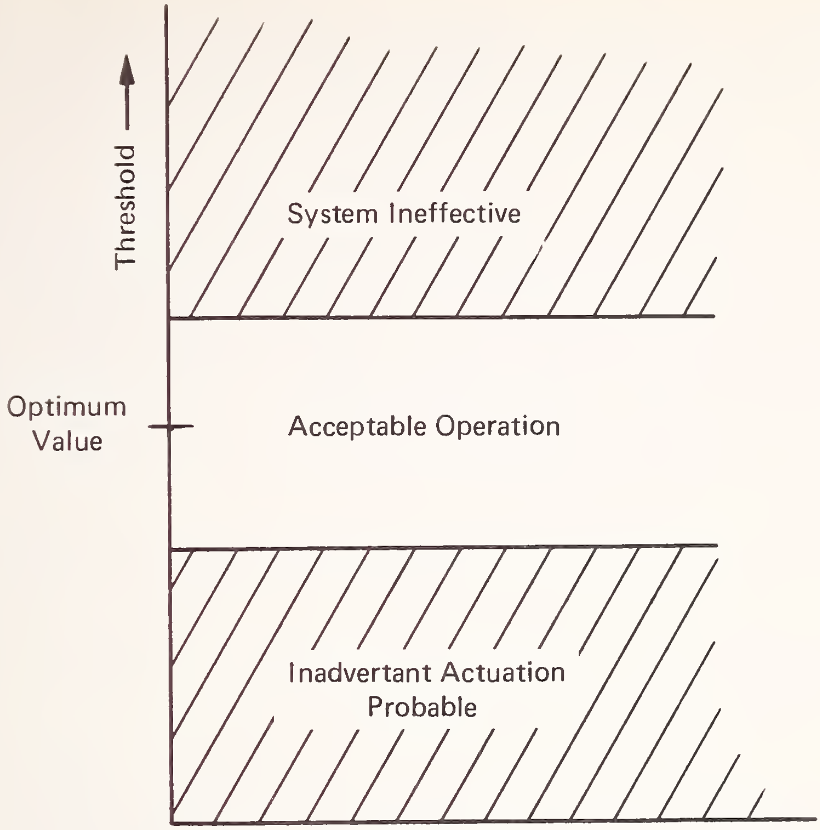


Figure 6.1. - Consequences of variation of threshold.

6.2.3 Failure to Actuate

Although the false alarm, being the more dramatic event, is the failure mode most discussed, a system with a low probability of actually deploying in collisions would be of concomitantly little value. The two most immediate concerns are likely to be with weather (ice, mud, etc. on the antennas) and targets which are characterized by too low reflectivity. While these are areas which will require substantial engineering effort, they do not appear to represent insoluble problems. It should be noted that a system which fails to actuate on some targets - 10% to 25% of the total - can still provide a level of protection far superior to anything now available.

Here, too, a major challenge is the possibility of circuit malfunction. Referring again to Figure 6.1, it is also possible for the threshold to drift upward toward the region of system ineffectiveness. Quite possibly both this and the related false-alarm problem can be partially mitigated by self-

testing circuitry, warning indicators, and fail-safe design. However, in view of the substantial cost of dynamic passive restraint systems, performance will have to be of a high order to be both cost-effective and acceptable to the public.

In this connection, one other failure mode deserves mention. Should the fears of the public not be sufficiently alleviated, or even be aggravated by unfortunate experiences with early systems, there could be a serious problem of deliberate system disablement. This will almost certainly be easy to accomplish, and could - in the extreme case - lead to a situation not unlike that for present active restraints: the system goes unused. The difference would be that the passive restraints will represent a substantially greater investment. Thus, it is of great importance that the first systems to come into general use be based upon particularly high standards of engineering, fabrication, testing, and installation.

6.3 SUMMARY AND CONCLUSIONS

6.3.1 Conclusions of the Present Study

This investigation is now at its midpoint. Our examination of the environmental, technical, and practical constraints associated with anticipatory crash sensing make clear the magnitude of the problem. At the same time, the potential benefits - even in terms of present restraint systems - are substantial. Microwave sensing appears basically feasible, but with the limitation that there will inevitably be classes of targets for which satisfactory response is not obtained. The goal of nearly zero inadvertent actuations with greater than 75% effectiveness may be obtainable, although the reliability and environmental specifications could affect cost so drastically as to make anticipatory sensing impractical.

Also, questions of legal liability can not be avoided. If there are known failure modes - both false alarm and non-deployment - motorists might well institute numerous lawsuits unless prior warning is given. Similarly, injury caused by the restraints or - more likely - the <u>possibility</u> that injury was due to deployment rather than the crash, could cause endless legal wrangling. This problem is clearly beyond the purview of the Transportation Systems Center. However, it is mentioned here to indicate a potential serious obstacle to actual use of anticipatory sensors. The issue has already been raised in connection with systems relying upon impact sensors, and the predictive case is even more complex.

Use of hybrid microwave/mechanical sensor systems may well represent the best compromise, if cost permits. For example, one could use a low-threshold mechanical sensor in series with a microwave radar system. Both units would have to sense a collision for deployment. The radar would eliminate false alarms from road irregularities, and the impact sensor would not respond to small objects of high reflectivity. For added security, one could use a high-threshold mechanical sensor which required no other sensing for the case of large obstacles with low reflectivity. The advantage would be that the radar/impact combination could be designed for much more rapid response, so that the initial impact causes near-instantaneous triggering if preceded by a target indication from the radar. (Possibly a single two-stage mechanical sensor could be used.)

Acoustic systems have not been ruled out, but the problems associated with the propagation medium and the automobile environment render this technique less promising. Susceptibility to ambient noise, inter-vehicle interference, transducer weatherproofing, and hazard-related target discrimination all represent problem areas with no obvious low cost solutions.

6.3.2 Future Plans

The TSC FY71 effort in crash sensor development has yielded two important results. The first and most visible is a prototype microwave radar system, installed in a test vehicle, now undergoing evaluation. Less dramatic but possibly of even greater value is the development of a basic understanding of the overall anticipatory sensor problem. Together, these will form the basis of a program to optimize the TSC system and evaluate the effectiveness of anticipatory sensors in general. Three task areas are included.

a. Task I: Advanced Development and Optimization. The present system is based upon use of separate receiving and transmitting antennas with simple solid state circuitry to achieve velocity, position, and target discrimination in a particularly simple manner. Essentially, the sensor responds to targets which are highly reflective for microwave energy. What must now be determined in detail is the degree to which this characteristic may be used to discriminate between those targets for which restraint system deployment is desirable and those for which it is not. Nearly half of the objects truck by automobiles are other automibiles, and these are expected to provide good reflection characteristics. However, it is less clear what response will be obtained for trees, telephone poles, abutments, etc. Thus, many further

measurements will be taken of such potential targets to determine the basic effectiveness of the sensor. Similarly, many tests are needed on obstacles for which deployment is not desired--people, animals, pavement defects, curbs, etc. Such tests will reveal the need for circuit modifications and permit adjustment of the basic triggering threshold to a value which excludes virtually all "false alarms", while responding to a high percentage of "real" targets.

The existing system and instrumented vehicle permit data to be taken readily, as described in Section 4. A similar characterization will be carried out for the acoustic system. Special attention will be devoted to determination of effects of various noise sources. As test and evaluation continues, effort will be expended on specific improvement and optimization of system elements. Particular attention is to be devoted to antennas, where the most favorable beam patterns and type of antenna are to be determined, on both operation and economic grounds. This study will be both experimental and analytical.

A relatively standard horn antenna, as used in our experimental studies, is rather bulky for automobile mounting, and - with weatherproof "window" - may be relatively expensive, even in high volume. Particular attention will be given to use of planar slot-array antennas. For this application the entire antenna could be a plate-structure approximately 3 inches in diameter (or a comparable rectangle) with a thickness of less than ¼ inch, completely encased in a weatherproof material such as Teflon. At present, cost is difficult to estimate precisely, as the only prior applications have been in military missile systems. However, informal estimates for automotive applications have been under $3 per antenna even in modest volume. Also, tailoring of beam pattern is readily accomplished.

The reliability required of the overall restraint system, particularly with respect to inadvertant actuation, is extremely high, and represents one of the most challenging problem areas for an anticipatory sensor. Development of prototype circuitry designed to maximize reliability is necessary to determine the basic limits so imposed and the costs associated with achieving acceptable reliability, if possible. A study will be undertaken to delineate optimal circuit design and fabrication technology

for sensors of the type developed at TSC. This will provide a firmly based estimate of the cost (in high-volume) of sensors meeting a range of reliability requirements.

b. <u>Task II: System Effectiveness</u>. With increasing data as to the classes of targets for which effective actuation can be obtained, it will increasingly be possible to compare results to accident data, thus making possible a reasonable estimate of the ultimate effectiveness of anticipatory sensors, assuming basic circuit operation reaches the ideal. An inherent limitation in this effort will be the paucity of relevant accident data, but it is expected that sufficient precision for these purposes will be possible. A number of serious questions arise when one considers not merely a single anticipatory sensor, but rather (ultimately) as many as 100 million units in use. It is this aspect that renders the basic reliability constraint so extreme. While other factors may also assume importance in the course of the effort, two are already apparent:

1. The power level of the microwave transmitter is relatively low in the prototype, and could be substantially lower. The present trend is toward increasingly restrictive limits on allowable radiation density. While the system could operate on very low intensity signals, this will increase receiver cost, and--far more important--make the system far more vulnerable to environmental microwave and circuit noise. Considerably more insight will be gained by experimental and analytical studies which will be undertaken in FY72.

2. Inter-vehicle interference now appears to present a major but still soluble problem under conditions of widespread use. Continuing study of actual system characteristics and performance will be carried out to permit a more definitive conclusion as to the magnitude of this problem and the probable merit of various ways of dealing with it.

As is implicit above, there are many problems associated with the use of anticipatory systems. It is by no means clear that their effectiveness can be evaluated by a small number of barrier crashes. It appears highly desirable to develop special additional test

procedures for such cases, and determination of meaningful tests will be complex. The question of the desirability and nature of such tests will be explored, and test procedures recommended, if found appropriate.

c. Task III: Study of Hybrid Systems. The numerous potential problem areas associated with anticipatory sensors are clear. However, whether or not the basic system proves suitable to general application, it is quite likely that a hybrid radar-mechanical sensor might do much to alleviate the problems by which each type is individually plagued. This topic, discussed in Section 6.3.1, will be carefully examined.

APPENDIX I
COLLISION DYNAMICS - A SIMPLIFIED MODEL

A greatly simplified analysis of the one-dimensional motion for an occupant of a vehicle undergoing collision with a fixed barrier can be made as follows.

Assume that, at time t=0, [Figure AI.1(a.)] the vehicle is traveling at speed v when it first contacts a solid, unyielding brick wall.

Assume that a restraint device, such as an air bag, is deployed in time τ , [Figure AI.1(b.)] and that the occupant undergoes no appreciable deceleration until the deployment is complete at $t=\tau$. The distance he travels in time τ is the deployment distance, ℓ_D. The car, however, is experiencing some amount of crush during thistime.

Assume that the occupant's center of gravity undergoes a uniform deceleration, α , starting at time τ [Figure AI.1(b.)] and continuing until he comes to rest, at time $t=\tau$ [Figure AI.1(c.)] . The distance he travels is the useable deceleration distance, ℓ_U, and consists partly of additional vehicle crush and partly of occupant movement into the restraint system.

The useable deceleration distance, ℓ_U, is related to initial velocity, v , deceleration, α , and deceleration time, $T-\tau$, as follows:

$$\ell_U = v\,(T-\tau) - \tfrac{1}{2}\alpha(T-\tau)^2 \qquad (1)$$

If the deceleration α is to bring the occupant to rest within the distance ℓ_U, v cannot exceed v_o, given by:

$$v_o = \alpha\,(T-\tau) \qquad (2)$$

That is, v_o is the maximum initial velocity for which the occupant can be brought to rest within the stated constraints on α , ℓ, and τ , and will be referred to as the "maximum allowed velocity". For a vehicle and restraint system characterized by those values of α , ℓ, and τ , v_o will be a measure of the maximum tolerable or survivable impact speed. Substituting Equation 2 into Equation 1 and rearranging so as to eliminate time,

$$\ell_U = \frac{v_o^2}{2\alpha} \qquad (3)$$

or,

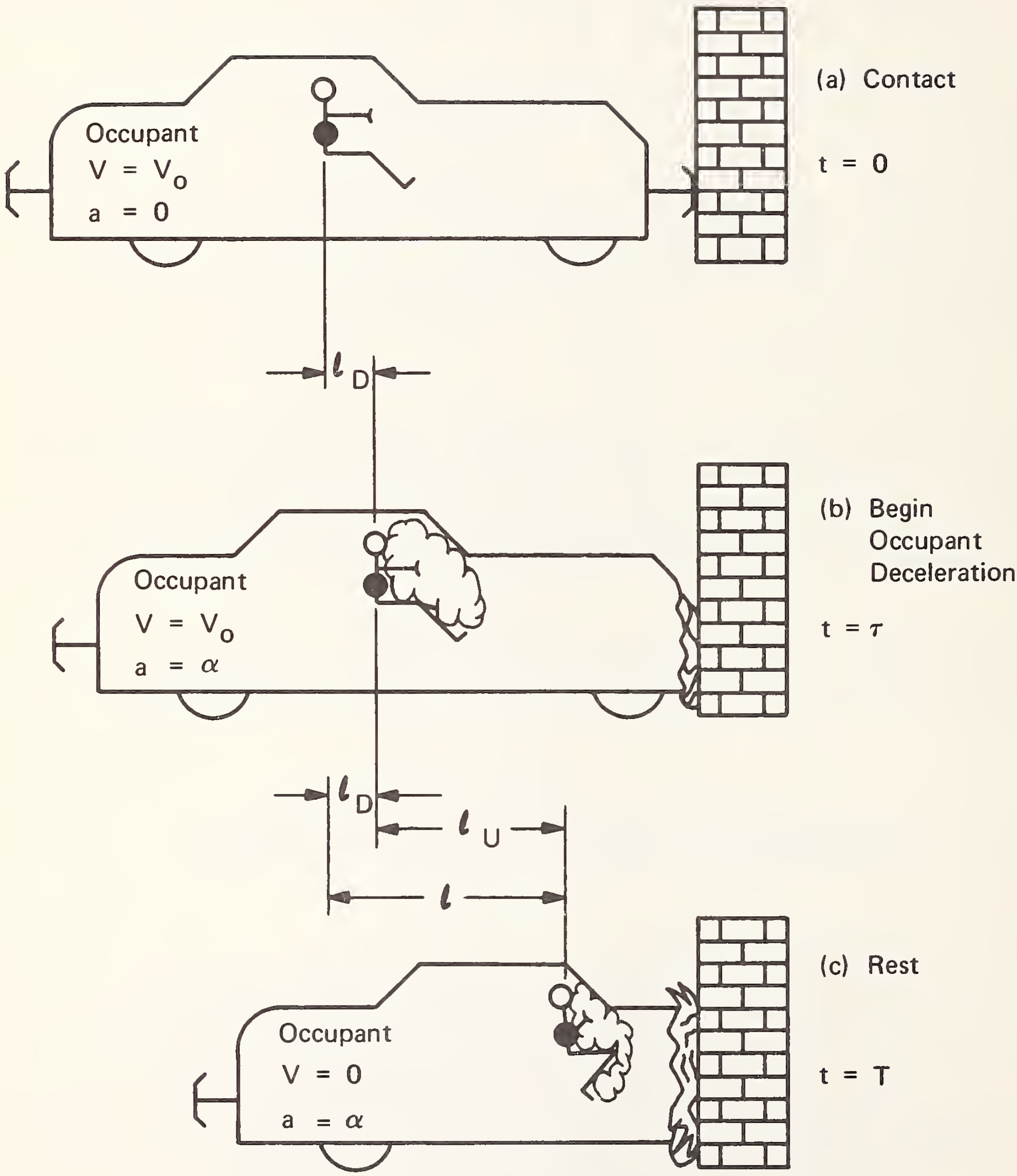


Figure AI.1(a.),(b.),(c.).- Simplified crash sequence.

$$v_o = \sqrt{2\alpha \ell_U} \qquad (4)$$

The deployment distance, ℓ_D, is merely

$$\ell_D = v_o \tau \qquad (5)$$

The total distance that the occupant travels, ℓ, beginning at $t=0$, is

$$\ell = \ell_D + \ell_U = v_o \tau + \frac{v_o^2}{2\alpha} \qquad (6)$$

Rearranging Equation 6,

$$v_o^2 + 2\alpha\tau v_o - 2\alpha\ell = 0 \qquad (7)$$

which is a quadratic equation in v_o . The positive root is

$$v_o = -\alpha\tau + \sqrt{\alpha^2 \tau^2 + 2\alpha\ell} \qquad (8)$$

Note that Equation 8 becomes Equation 4 when $\tau = 0$ and when $\ell = \ell_U$.

When v is expressed in miles per hour, α in G's, τ in milliseconds, and ℓ in feet, Equation 8 becomes

$$v_o = -21.954\text{X}10^{-3}\alpha\tau + \sqrt{482\text{X}10^{-6}\alpha^2\tau^2 + 29.9\alpha\ell} \qquad (9)$$

Equation 9 was used to plot several sample curves of v_o versus ℓ, and of v_o versus τ , for various values of α . These plots appear in Figures AI.2 through AI.9 and should be self-explanatory. Caution should be used in comparing large velocity differences for constant ℓ , as in the real crash situation ℓ is a function of v_o , in addition to being a function of the construction of the particular vehicle.

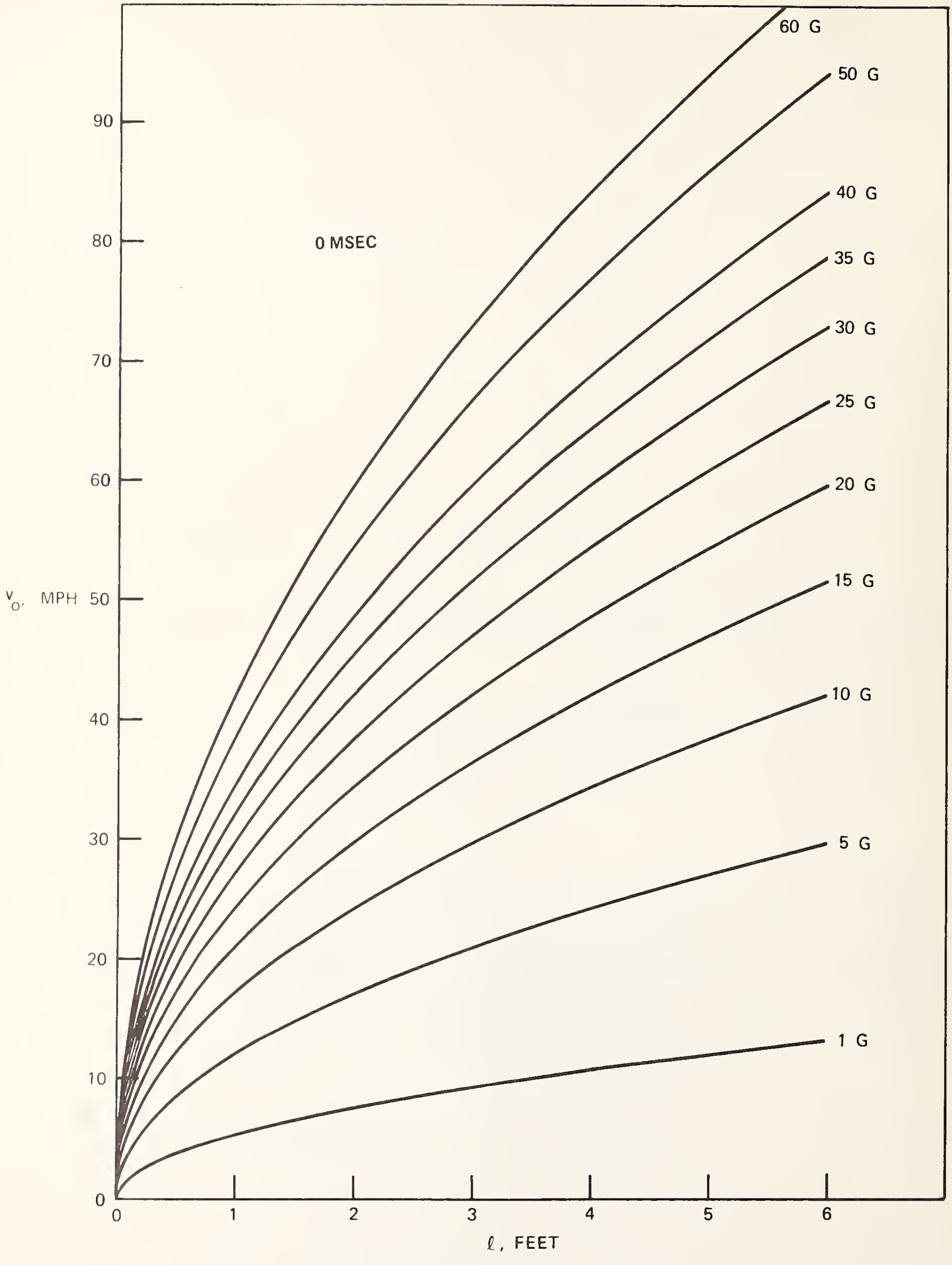


Figure AI.2.- Maximum allowed velocity vs. crush distance for various τ.

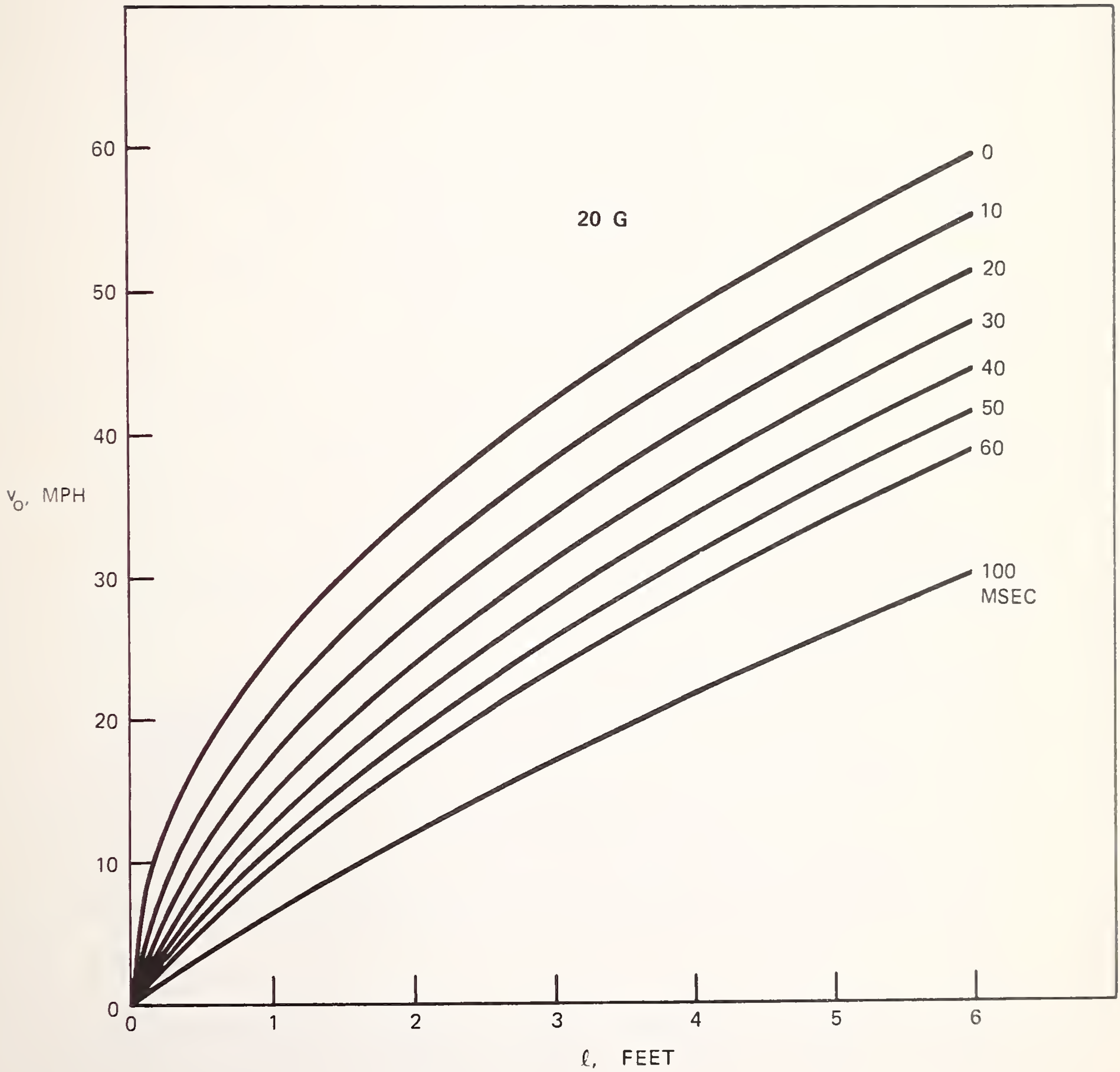


Figure AI.3.- Maximum allowed velocity vs. crush distance for various τ .

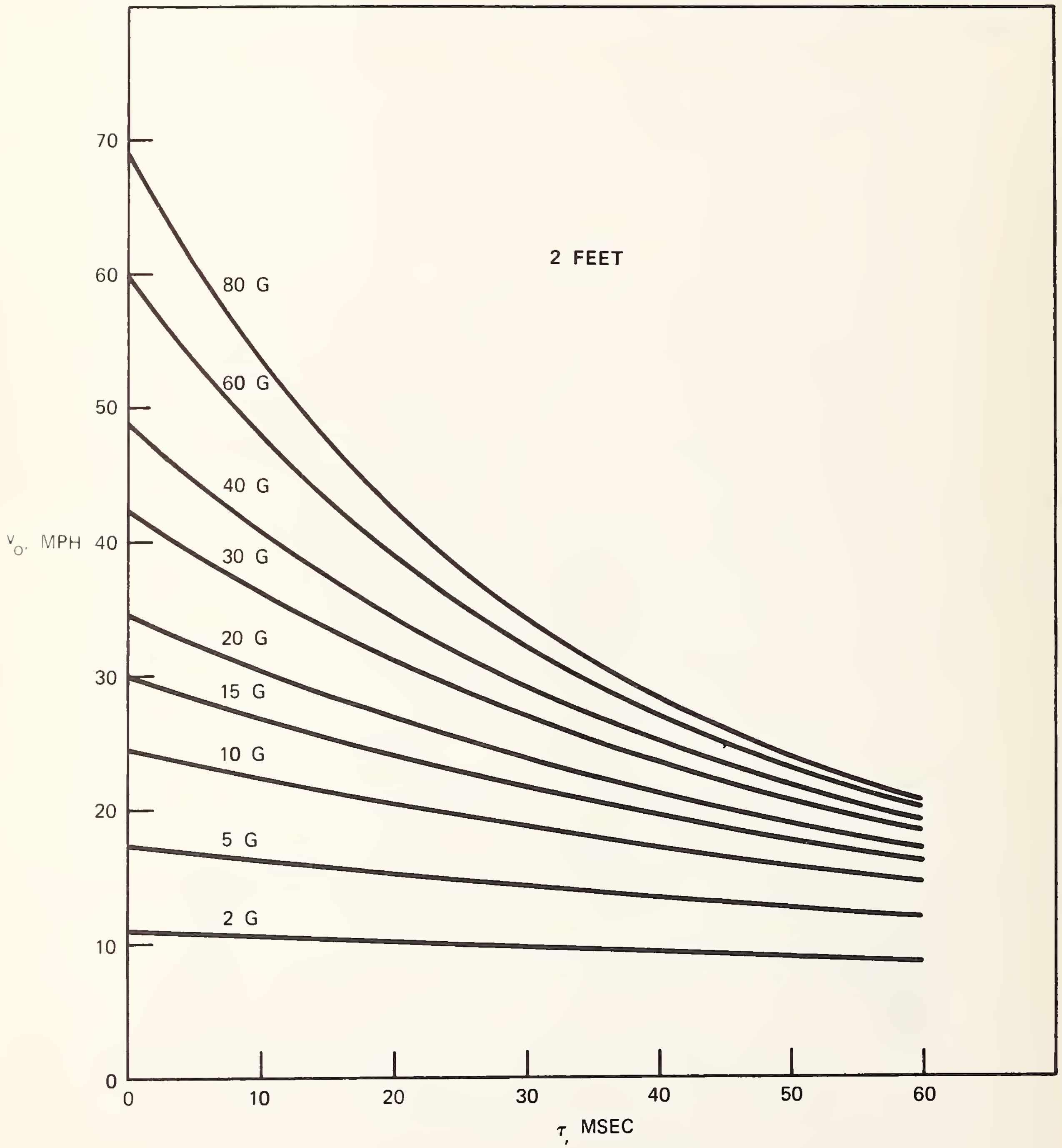


Figure AI.4.- Maximum allowed velocity vs. delay time for various α (ℓ=2').

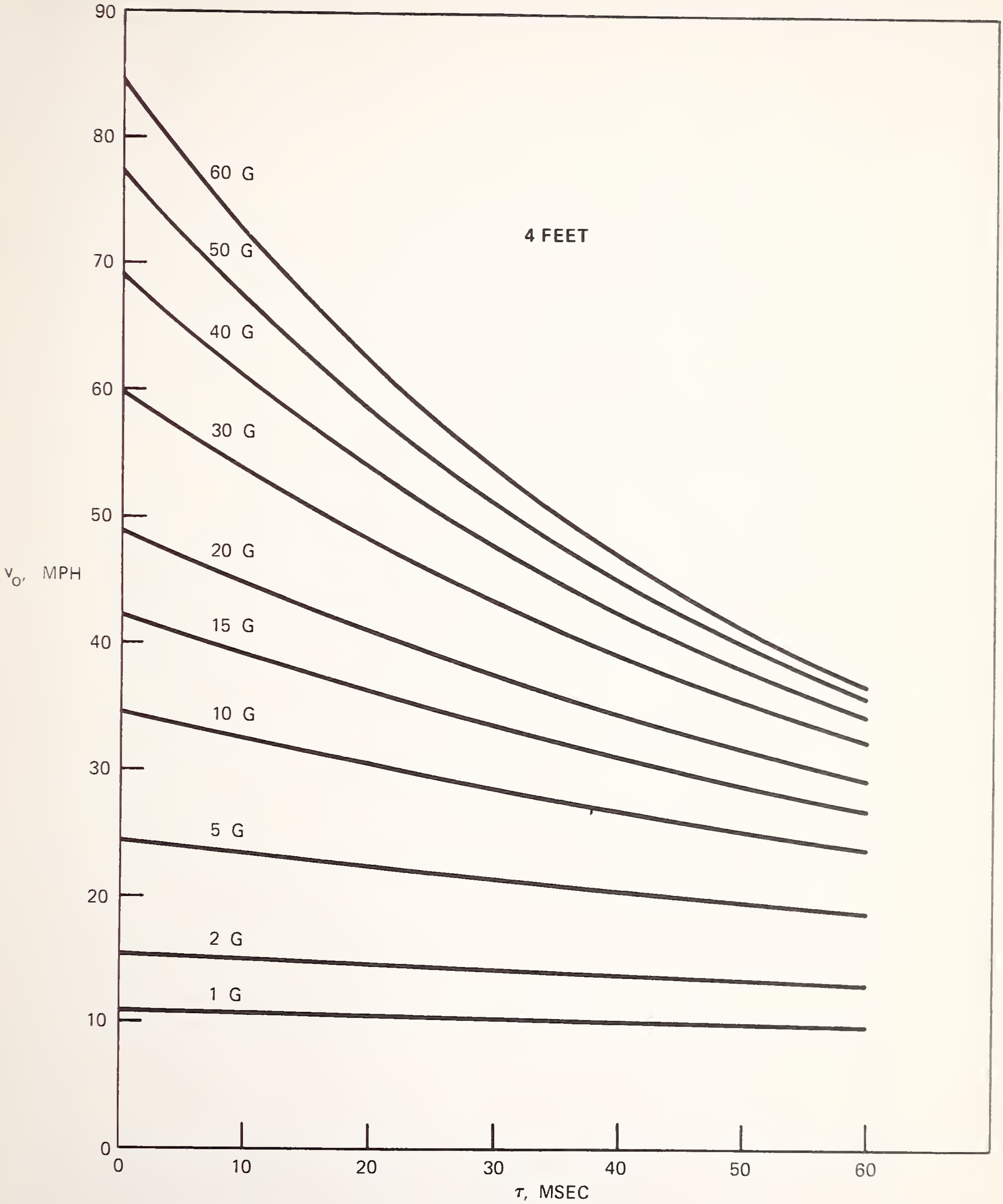


Figure AI.5.- Maximum allowed velocity vs. delay time for various α (ℓ=4').

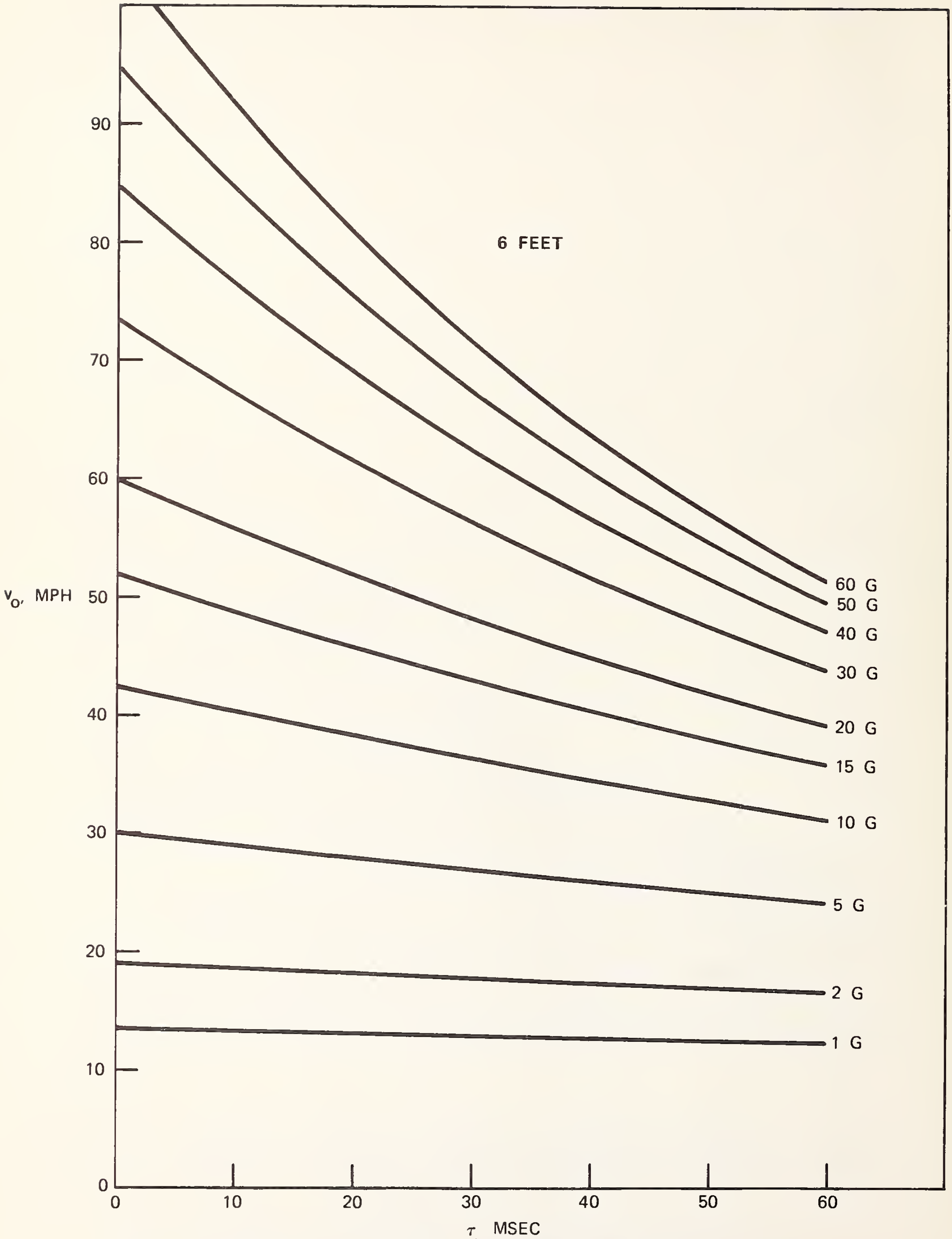


Figure AI.6.- Maximum allowed velocity vs. delay time for various α (ℓ=6').

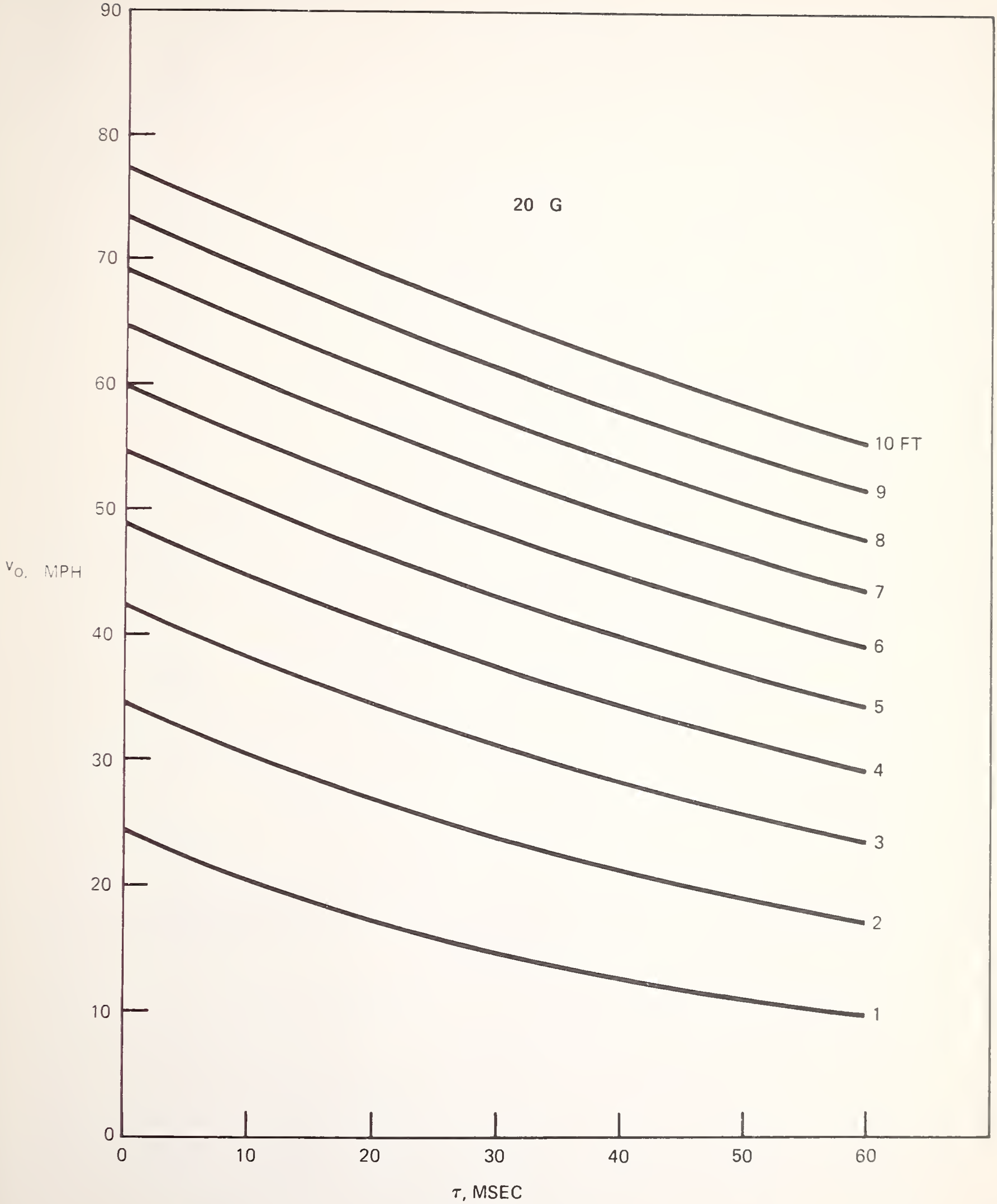


Figure AI.7.- Maximum allowed velocity vs. delay time for various ℓ (α=20G).

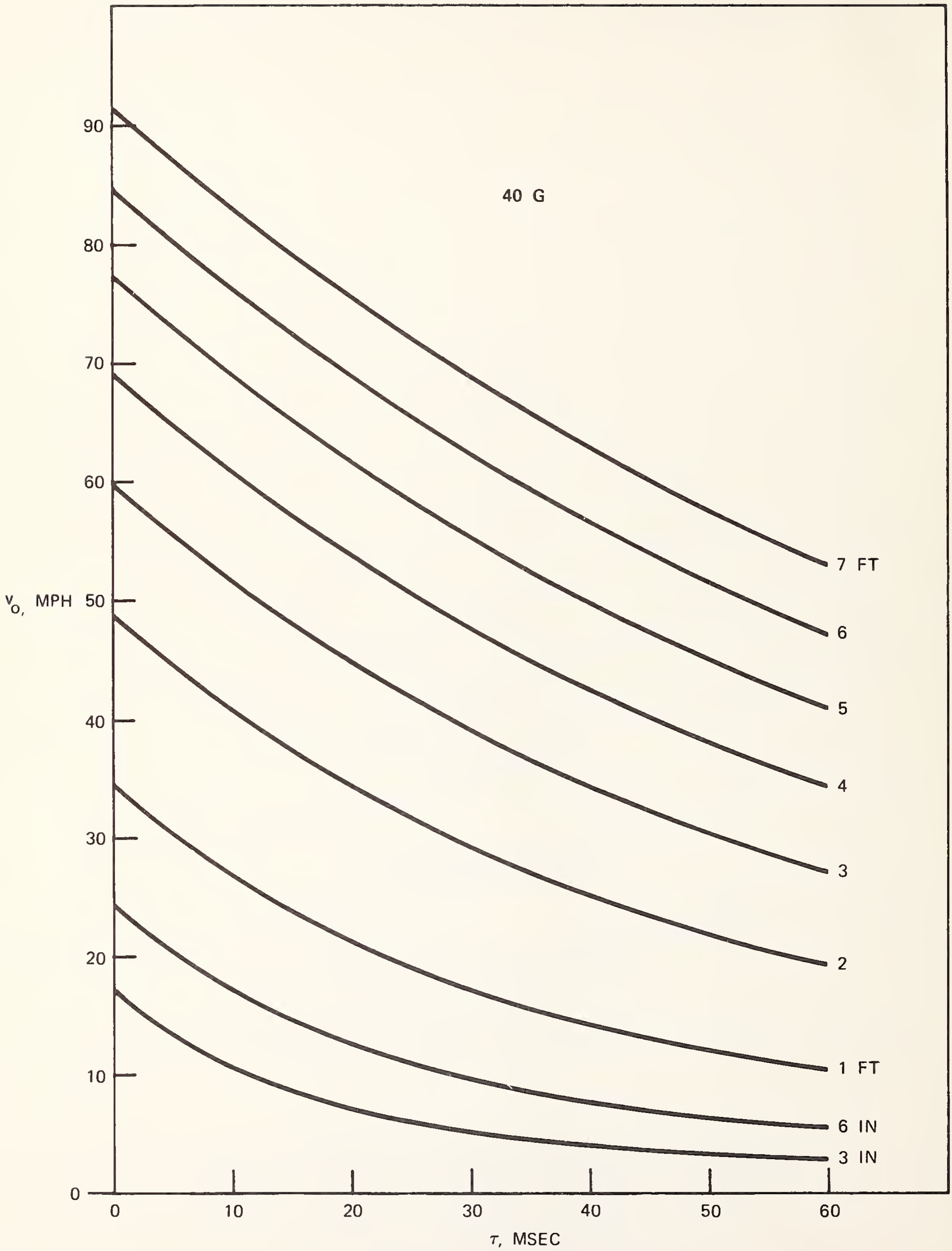


Figure AI.8.- Maximum allowed velocity vs. delay time for various ℓ (α=40G).

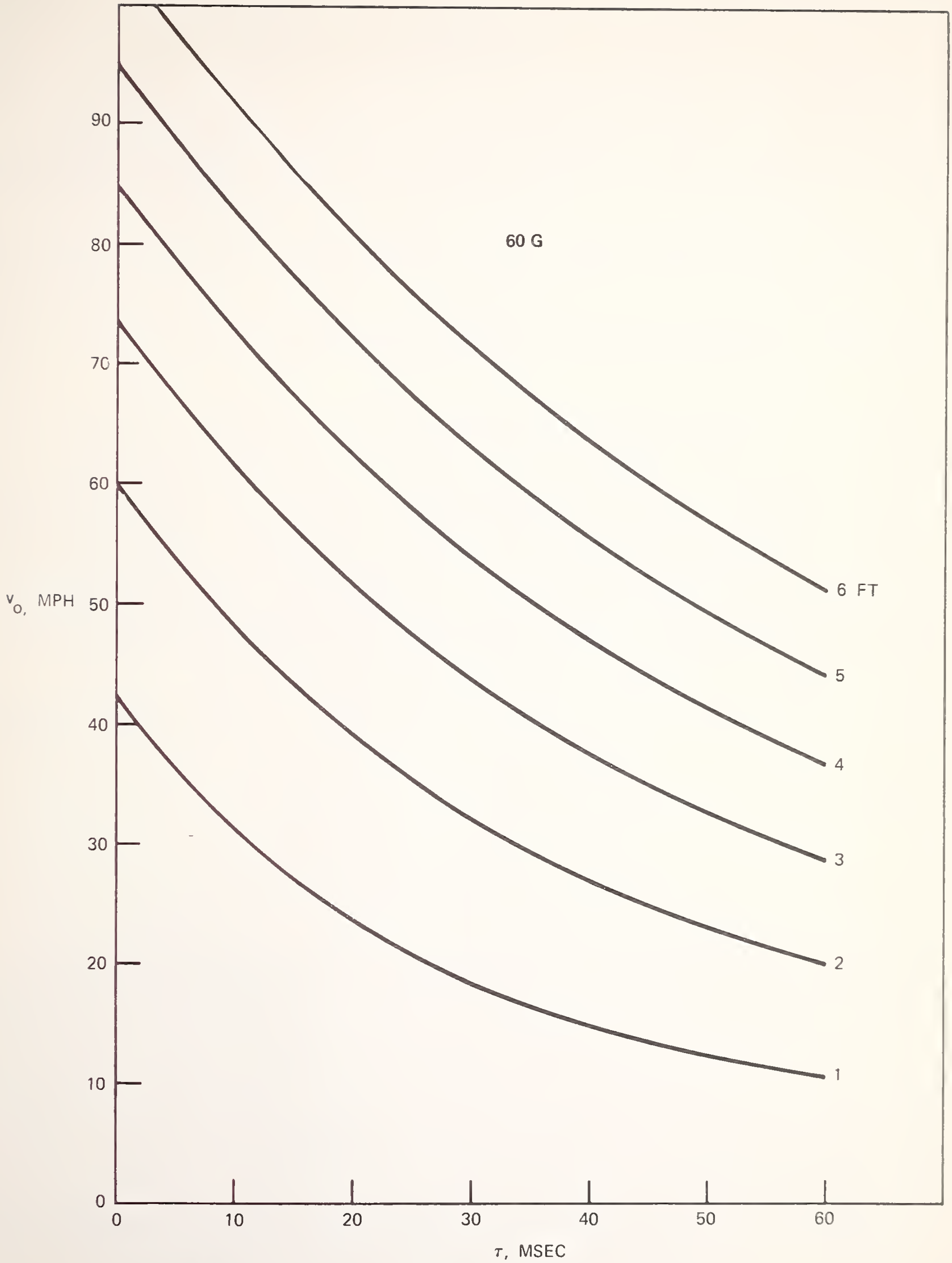


Figure AI.9.- Maximum allowed velocity vs. delay time for various ℓ (α=60G).

APPENDIX II
ESTIMATION OF SYSTEM EFFECTIVENESS

In evaluation of the effectiveness of dynamic passive restraint systems, one can define the following variables for accidents (collisions) of all types:

C_N, the cost of an accident when the restraint is not deployed;

C_D, the cost of an accident when the restraint is deployed; and,

P_D, the probability that restraint deployment will occur.

The definition of the cost of an accident is complex, being in part a value judgement. Fortunately, for the purposes of this discussion it need not be defined further. However, note that it can be expressed simply in terms of number of deaths (or injuries); economic cost is not necessarily implied. In the remainder of this treatment, it will be taken as number of lives lost-per-accident, but monetary cost can be obtained merely by multiplication by whatever cost factor is chosen as appropriate.

C_N, C_D, and P_D are all complicated functions of many variables. That is,

$$C_N = C_N\ (x_1,\ x_2, \ldots x_n)$$

$$C_D = C_D\ (x_1,\ x_2, \ldots x_n)$$

$$P_D = P_D\ (x_1,\ x_2, \ldots x_n)$$

The variables x_i represent as many of the parameters of automobile accidents as is feasible or meaningful to include. Examples include impact velocity, impact angle, type of accident, and vehicle crashworthiness. The last will typically be a function of the first three, and there is a degree of interdependence among all. For the problem treated here, no attempt is made at estimation of accident probability, which would complicate the task immensely and introduce many more variables. Rather, N_A, the annual number of accidents of a type specified by a particular set of x_i, will be taken as data to be provided from actual accident statistics. $\left[N_A = N_A\ (x_1,\ x_2, \ldots x_n)\right]$.

Given this foundation, one may write a simple expression for C_A, the annual cost of accidents of a particular type:

$$C_A = N_A \left[P_D C_D + (1-P_D)\ C_N \right] = C_A (x_1,\ x_2, \ldots x_n) \qquad (1)$$

Nore properly, N_A is a multidimensional density, as is C_A, and equation (1) is better written:

$$C_A dx_1 dx_2 \ldots dx_n = N_A \left[P_D C_D + (1-P_D) C_N \right] dx_1 dx_2 \ldots dx_N \quad (2)$$

Total impact on auto safety is then obtained from integration over all accidents:

$$C = \underset{\substack{\text{all} \\ \text{accidents}}}{\int_1 \int_2 \cdots \int_n} N_A \left[P_D C_D + (1-P_D) C_N \right] dx_1 dx_2 \ldots dx_n \qquad (3)$$

Since the variables x_i are in many cases neither continuous nor completely quantitative, no such integration can actually be performed. However, sufficient discrete quantization is possible to write (3) as a summation over volume elements in x-space.

$$C = \sum_{i_1}^{m_1} \sum_{i_2}^{m_2} \cdots \sum_{i_n}^{m_n} N_{A_{i_1 i_2 \ldots i_n}} \left[P_{D_{i_1 i_2 \ldots i_n}} C_{D_{i_1 i_2 \ldots i_n}} + (1-P_{D_{i_1 i_2 \ldots i_n}})\ C_{N_{i_1 i_2 \ldots i_n}} \right] \qquad (4)$$

It is in this latter form (equation (4)) that evaluation will normally be carried out; a very simple computer program can do whatever processing is warranted by the data. In most cases the further assumption of product-form separability can be used:

$$C_N (x_1, x_2, \ldots x_n) = C_{N1} (x_1) \quad C_{N2} (x_2) \ldots C_{Nn} (x_n)$$

$$C_D (x_1, x_2, \ldots x_n) = C_{D1} (x_1) \quad C_{D2} (x_2) \ldots C_{D2} (x_n)$$

$$P_D (x_1, x_2, \ldots x_n) = P_{D1} (x_1) \quad P_{D2} (x_2) \ldots P_{D3} (x_n)$$

Analysis based on this formulation is inherently limited by the available data. Thus, it should be noted that great precision is neither feasible nor necessary. If a given class of accident is found to represent 4% of the total cost, with an uncertainty of 2%, this is acceptable; there would be no benefit to knowing that the true value is 3.17%. As indicated

previously, it is hoped that anticipatory dynamic restraint systems can apply to a significant number of cases and represent real improvement, but it is not expected that any answer developed here will have better than 25% to 50% accuracy as to the exact magnitude of that improvement. This should be adequate for the purposes of this study.

It is probable that for the case at hand the problem can be treated adequately through consideration of only four variables x·: velocity v impact angle θ, target detection characteristic D, and target crash severity S. The cost equations can then be written in terms of parameters

$$C_N = C_{N1}(v)C_{N2}(\theta)C_{N3}(S)$$

$$C_D = C_{D1}(v)C_{D2}(\theta)C_{D3}(S)$$

$$P_D = P_{D1}(v)P_{D2}(\theta)P_{D3}(D)$$

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